Status of the Higgs Boson Search at the ATLAS Experiment

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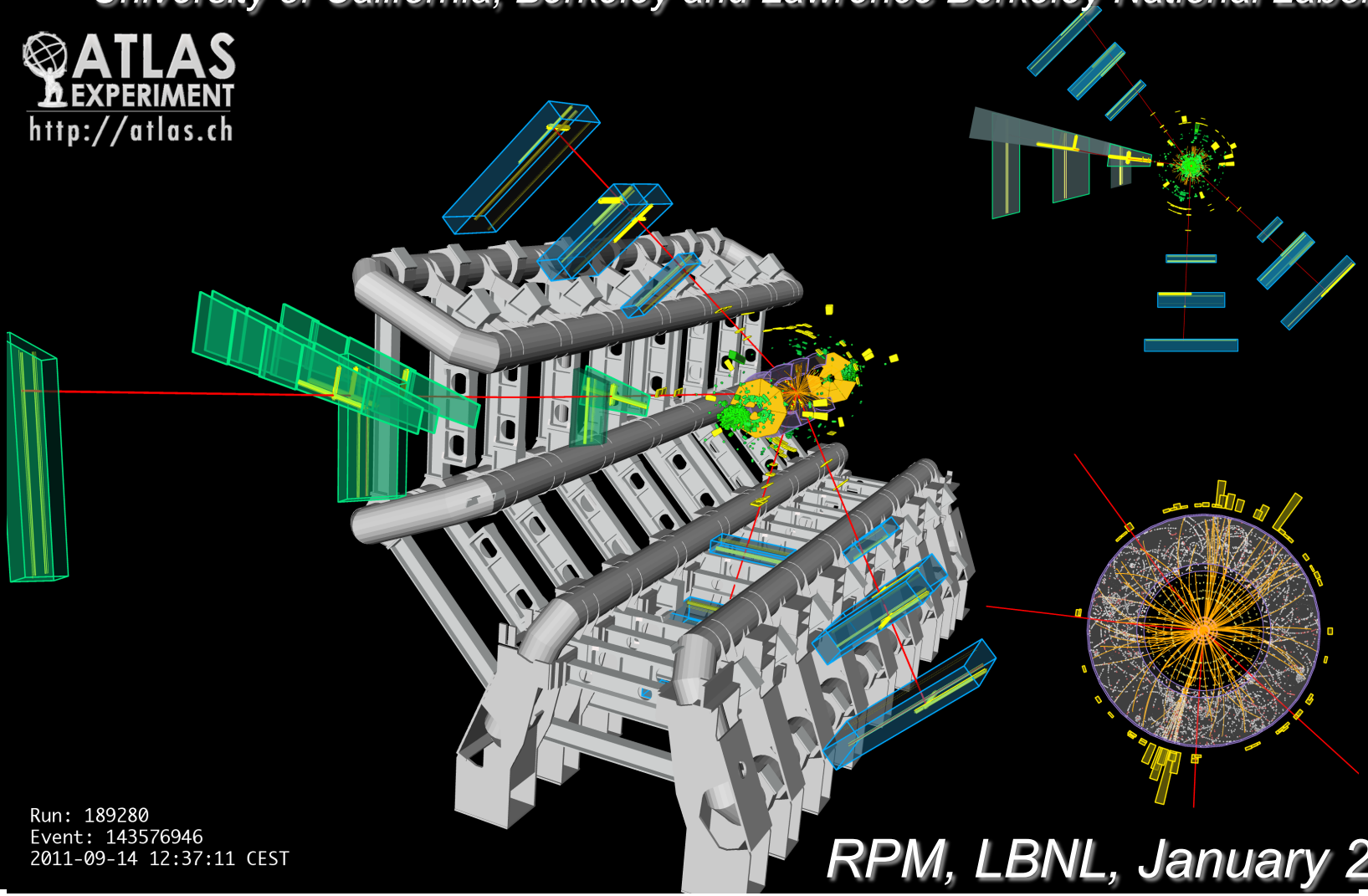
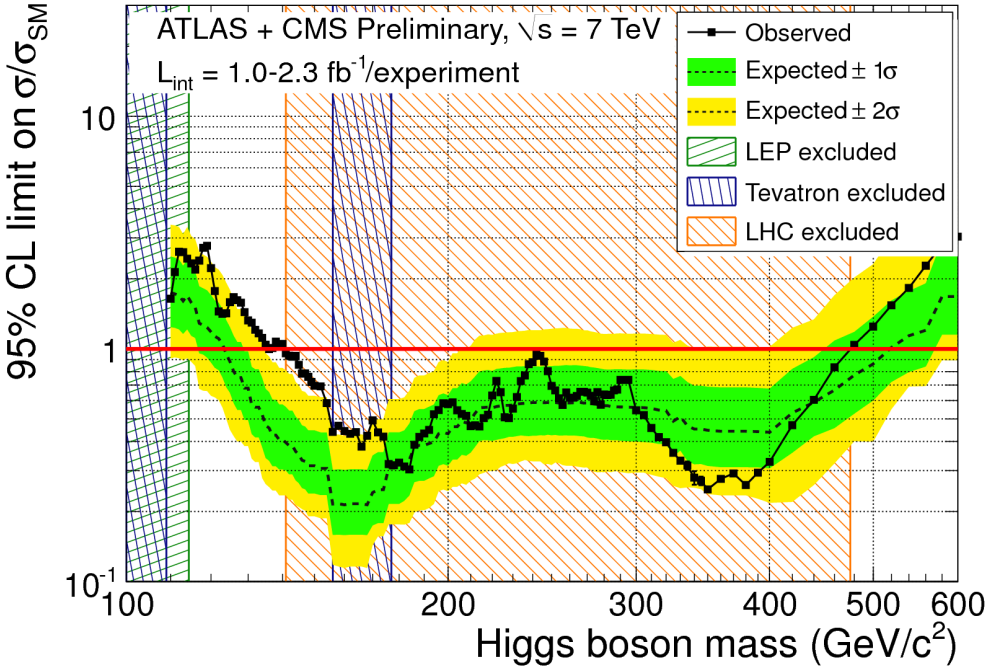
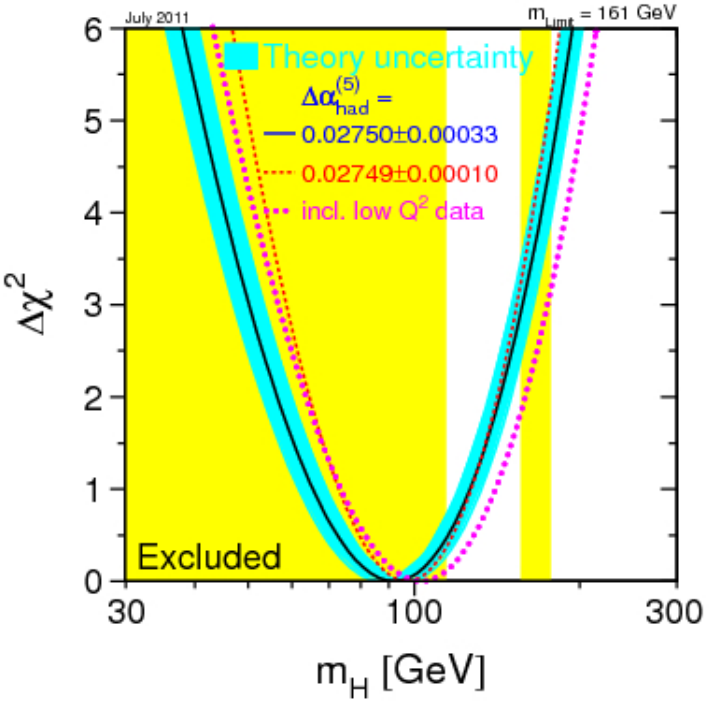


RPM, LBNL, January 2012

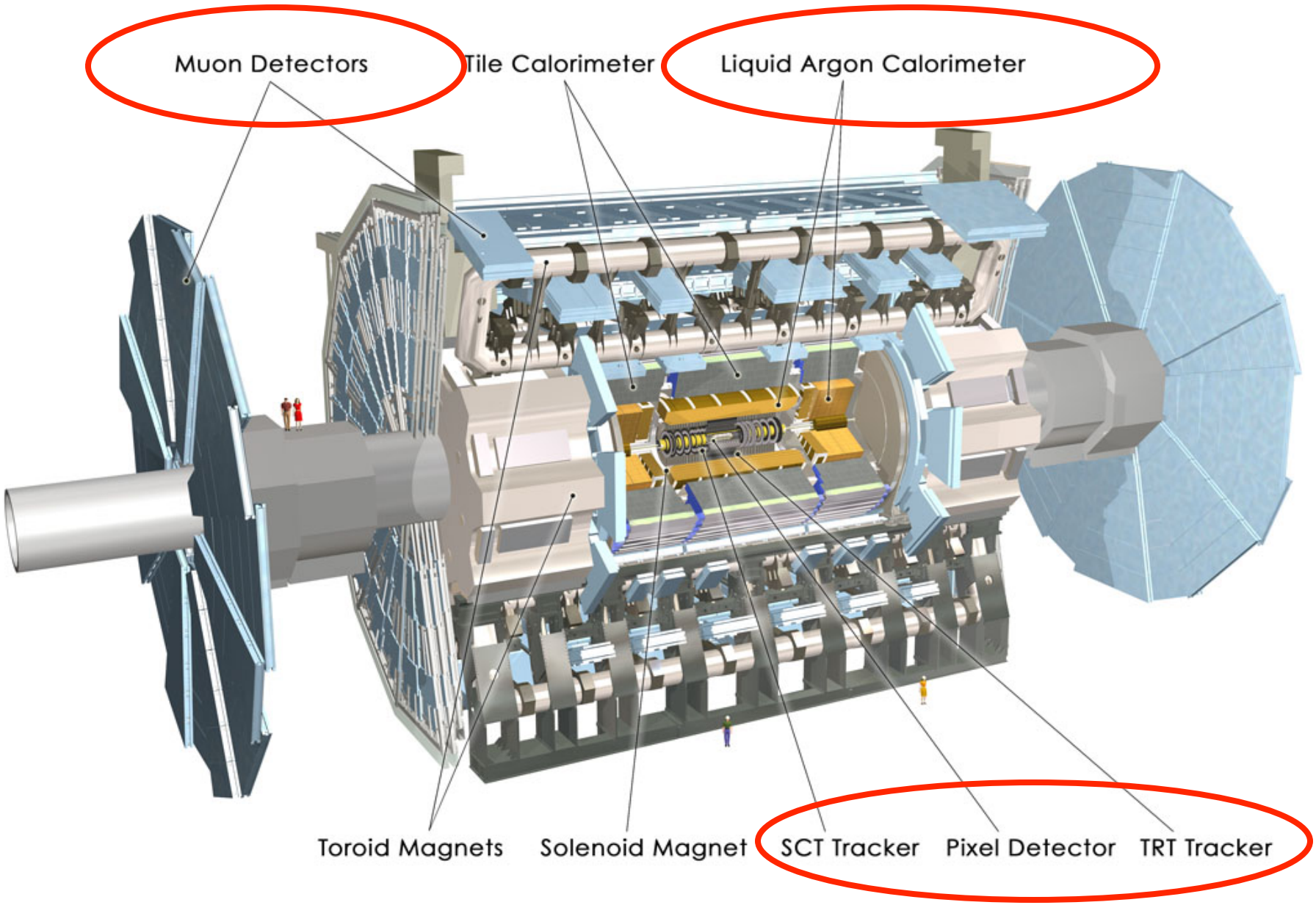
Introduction

- In the Standard Model the Higgs boson
  - is the only fundamental scalar particle
  - breaks the electroweak symmetry and gives mass to gauge bosons and fermions
  - has an unknown mass value but electroweak precision data prefer a low mass (<161 GeV at 95% C.L.)
  - is excluded below 114 GeV and between 141 and 476 GeV

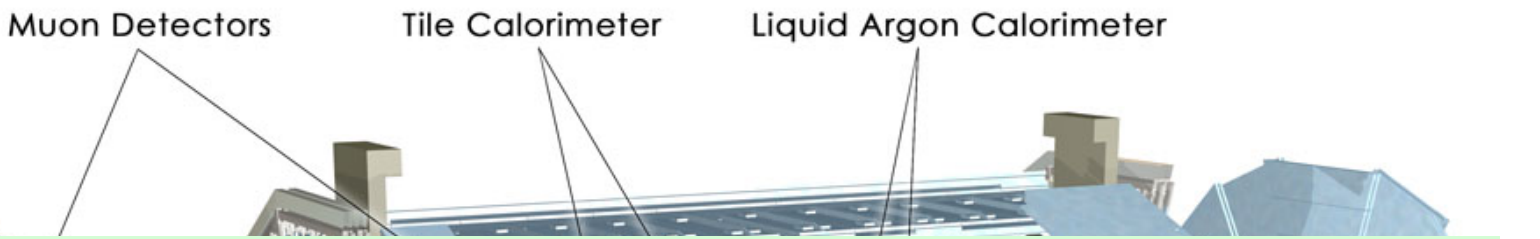




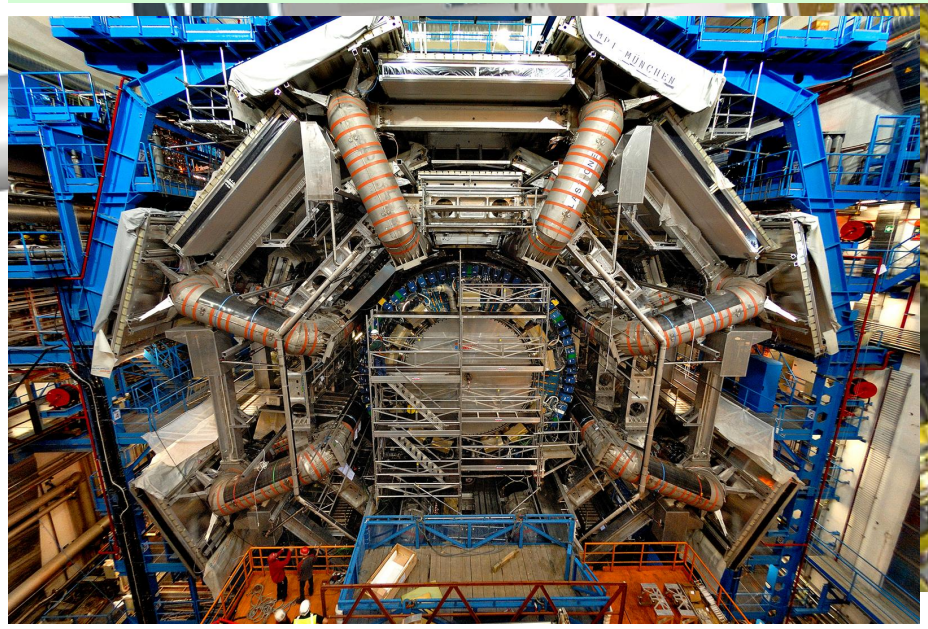
The ATLAS Detector

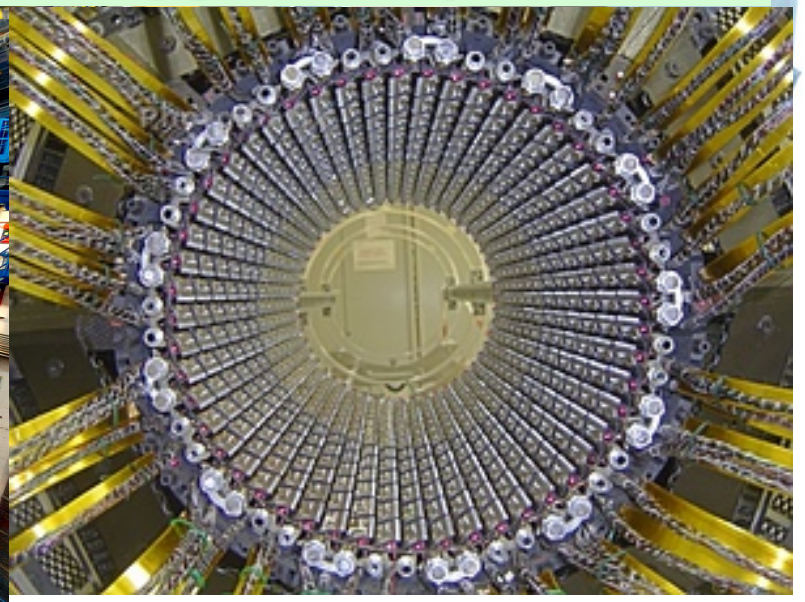


The ATLAS Detector



Muons detection and momentum measurement relies on Inner Detector and Muon Spectrometer: **σ(p)/p ≈ 2%** for muons from Higgs decay





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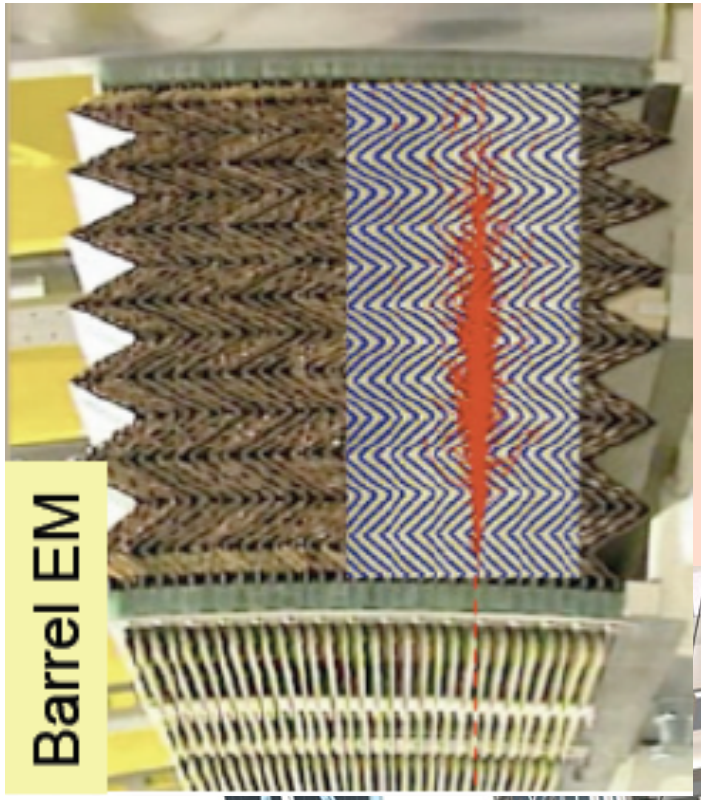
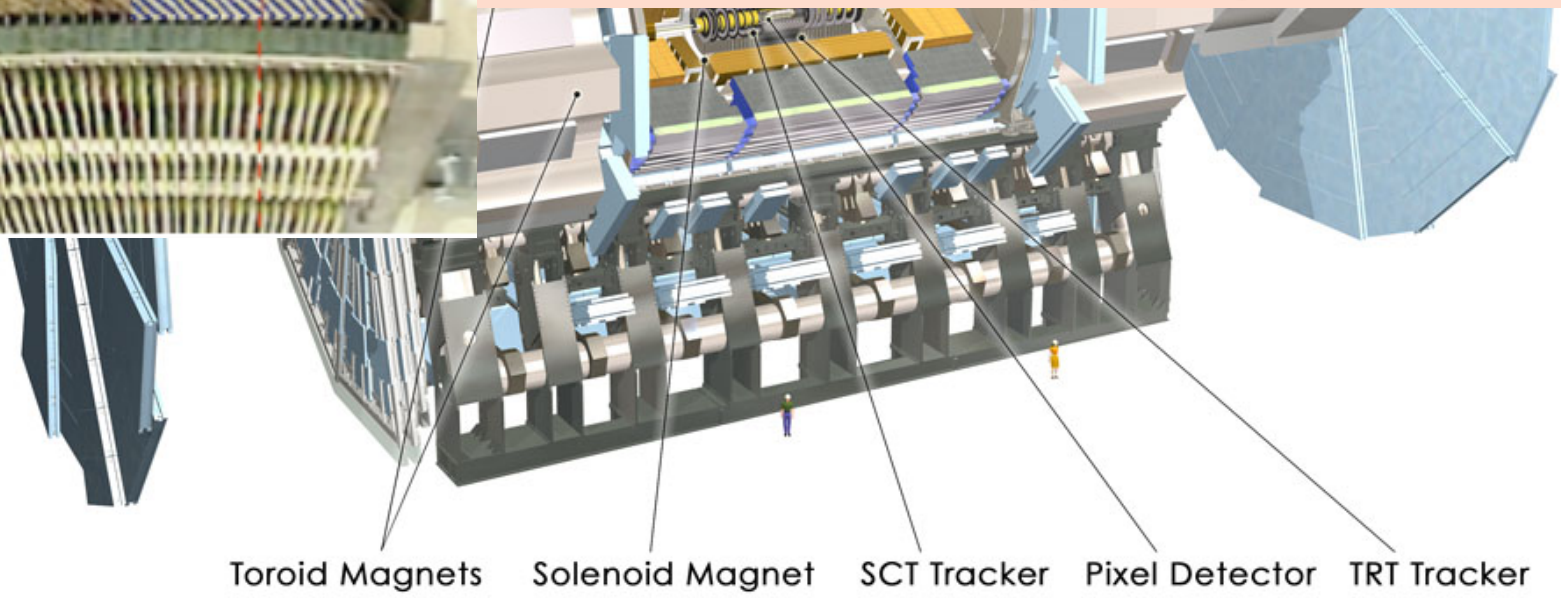
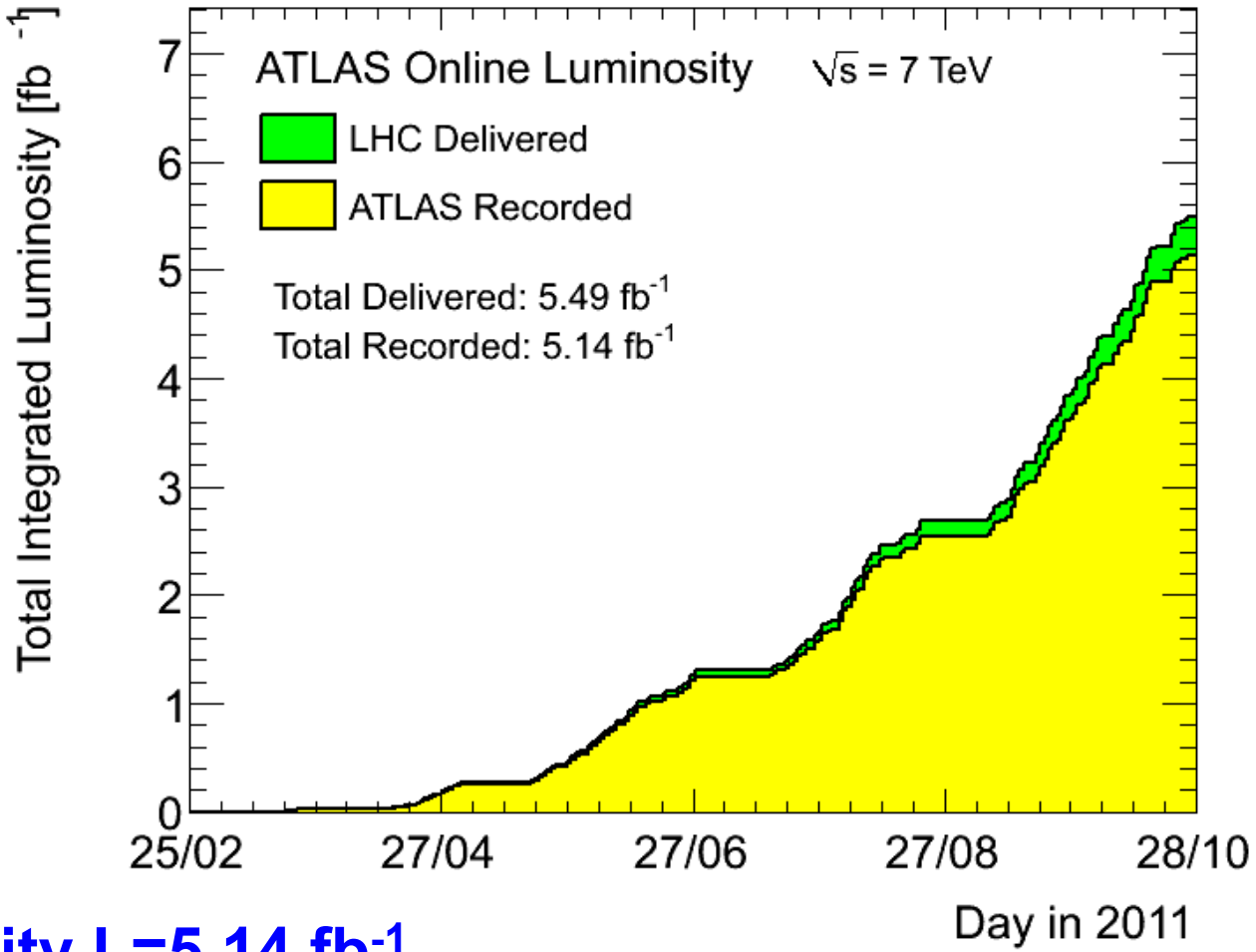


Photon and Electron identification and energy measurement relies on highly segmented LAr calorimeter: design is **$\sigma(E)/E = 10\text{-}15\%/\sqrt{E} \oplus 0.7\% \approx 1.4\%$** in relevant energy range



Luminosity

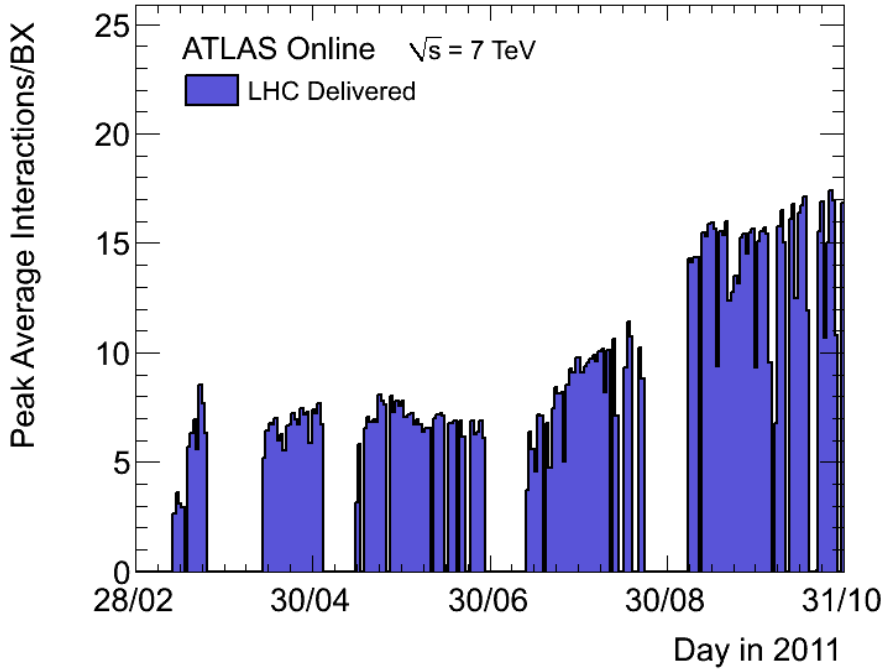


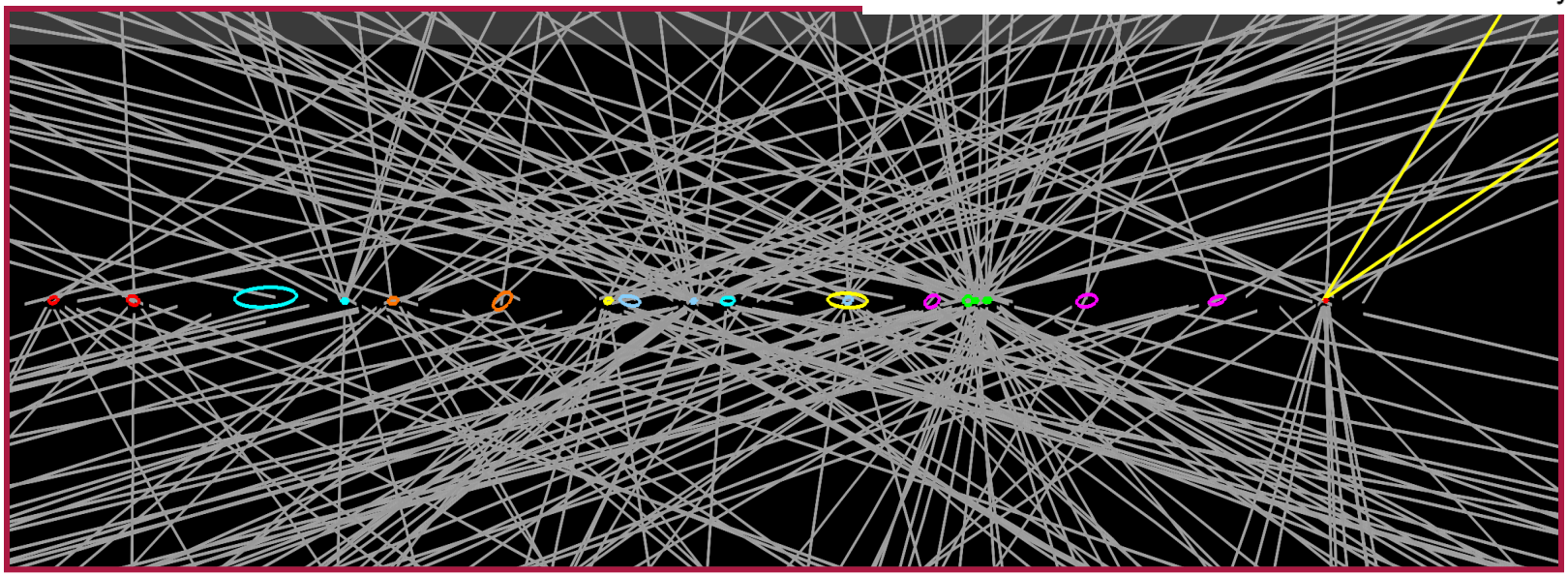
- **Recorded luminosity L=5.14 fb^{-1}**
  - **Data taking efficiency: 93.5%**
  - **Fraction of recorded data good for physics analysis: 90-96%**
  - **All subdetectors operate more than 96.5% of their channels**
- **Luminosity uncertainty is 3.9%**
  - **Determine from beam scans (S. van der Meer method)**

Pileup in 2011

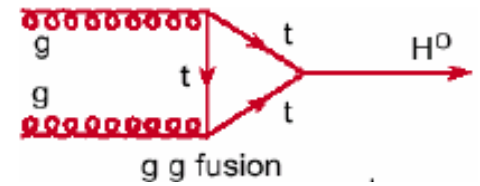
- Increase in number of pileup interactions due to
  - increase in beam currents
  - decrease of β* resulting in smaller beam size

$$\mu = \frac{n_1 n_2}{2\pi \Sigma_x \Sigma_y} \sigma_{inel}$$

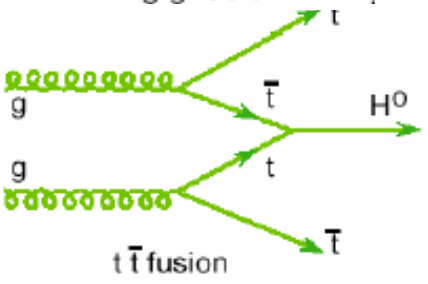




Higgs Production at the LHC

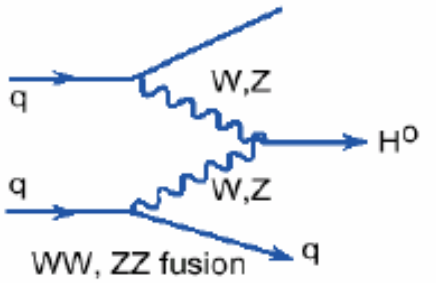


g g fusion

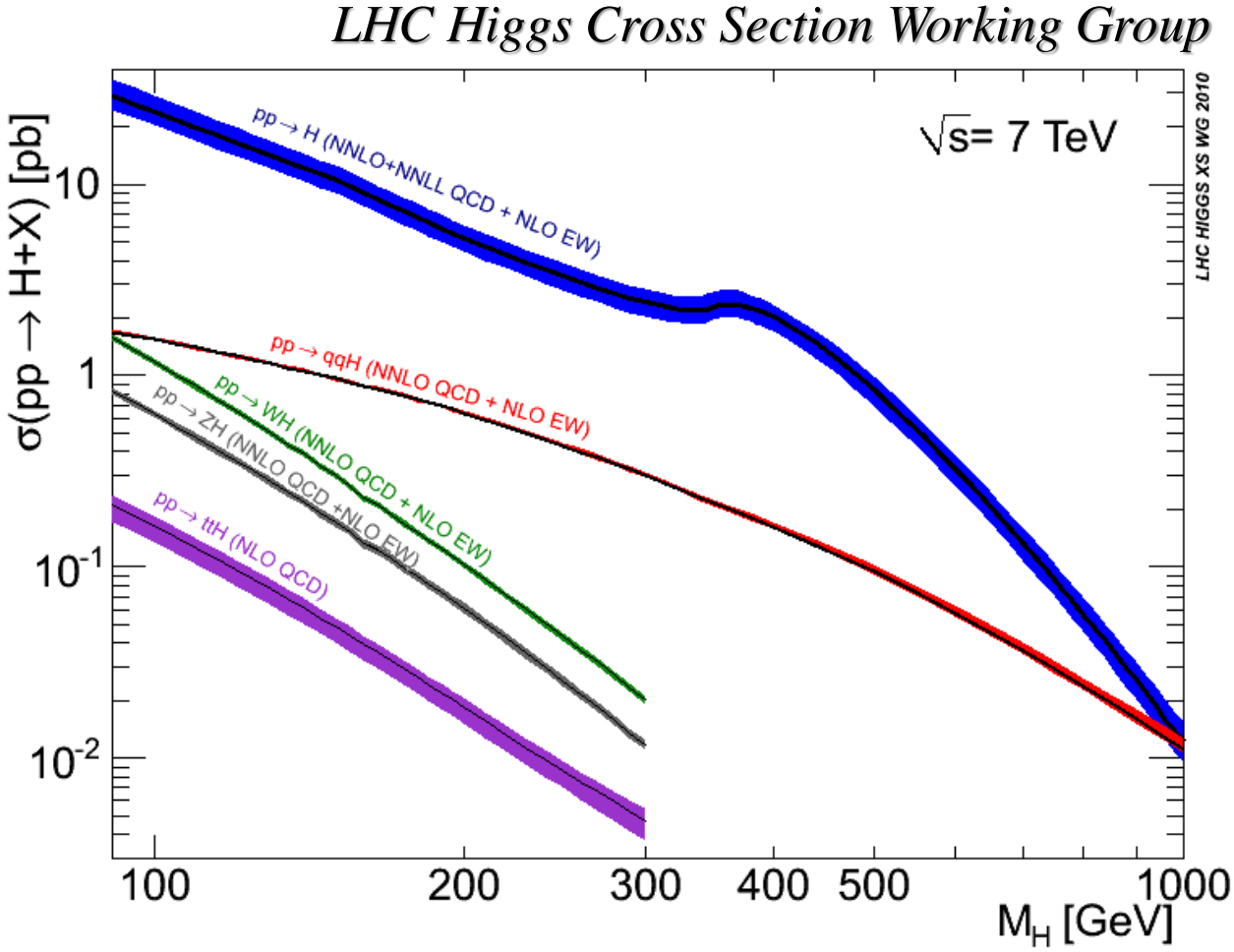


t t̄ fusion

W, Z bremsstrahlung



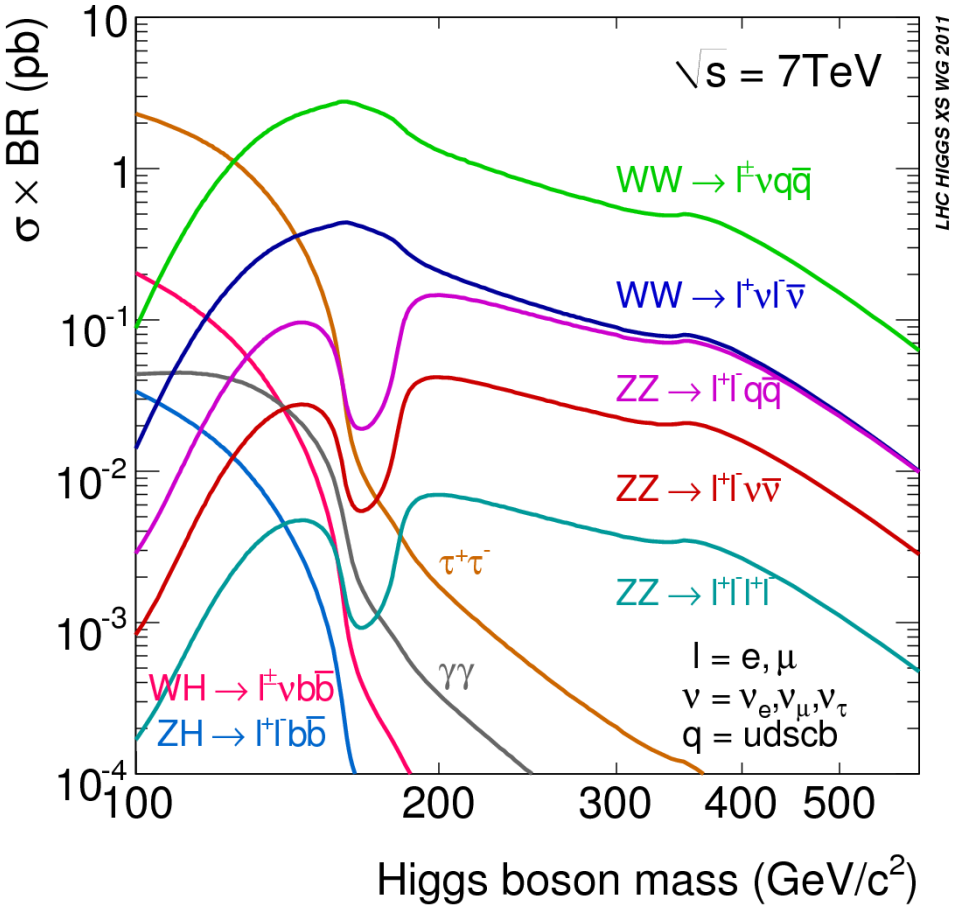
WW, ZZ fusion



- Cross section uncertainties typically 15%
  - Scale uncertainty 1-12%
  - PDF uncertainty 4-8%

Cross Section x Branching Ratio

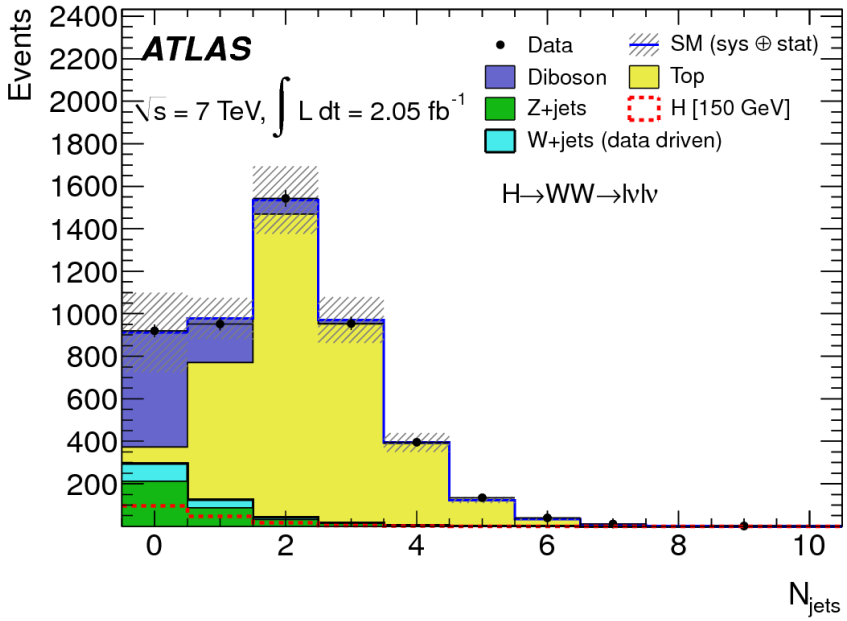
- High mass region:
  - WW and ZZ most important
- Low mass region:
  - ZZ->4 leptons
  - $\gamma\gamma$
  - $\tau\tau$, WW->lνlν

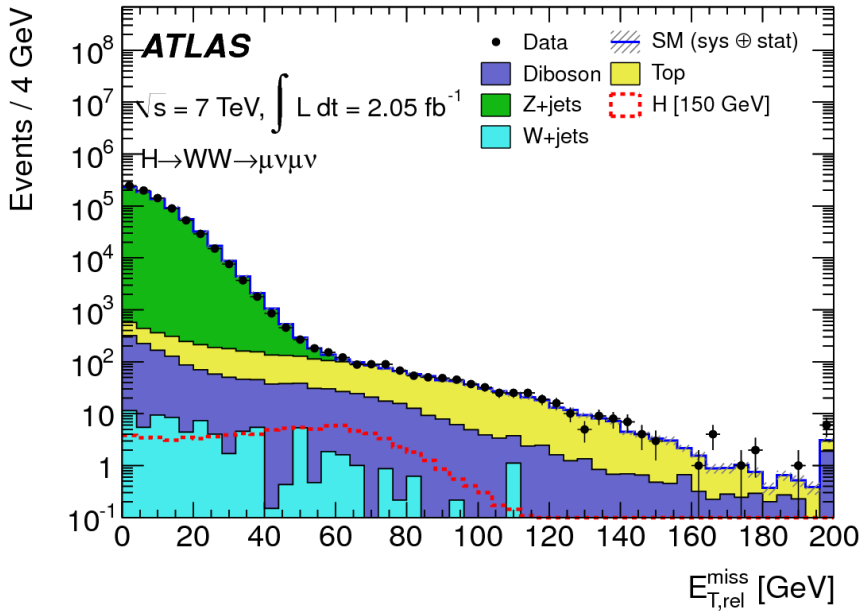


- Will focus here on low mass regime and on analyses with > 1 fb^{-1}:
  - WW, $\gamma\gamma$, ZZ->4 leptons

H->WW->lvlv Search

- For m_H=130 GeV: σ x BR = 170 fb => 340 events / 2 fb^{-1}
- Main backgrounds:
  - WW, ttbar and Drell-Yan production
  - Understanding of E_T^{miss} and low p_T jets critical
- Simple cut based analysis
  - Backgrounds validated in control regions
    - Extrapolated from control regions to signal using MC

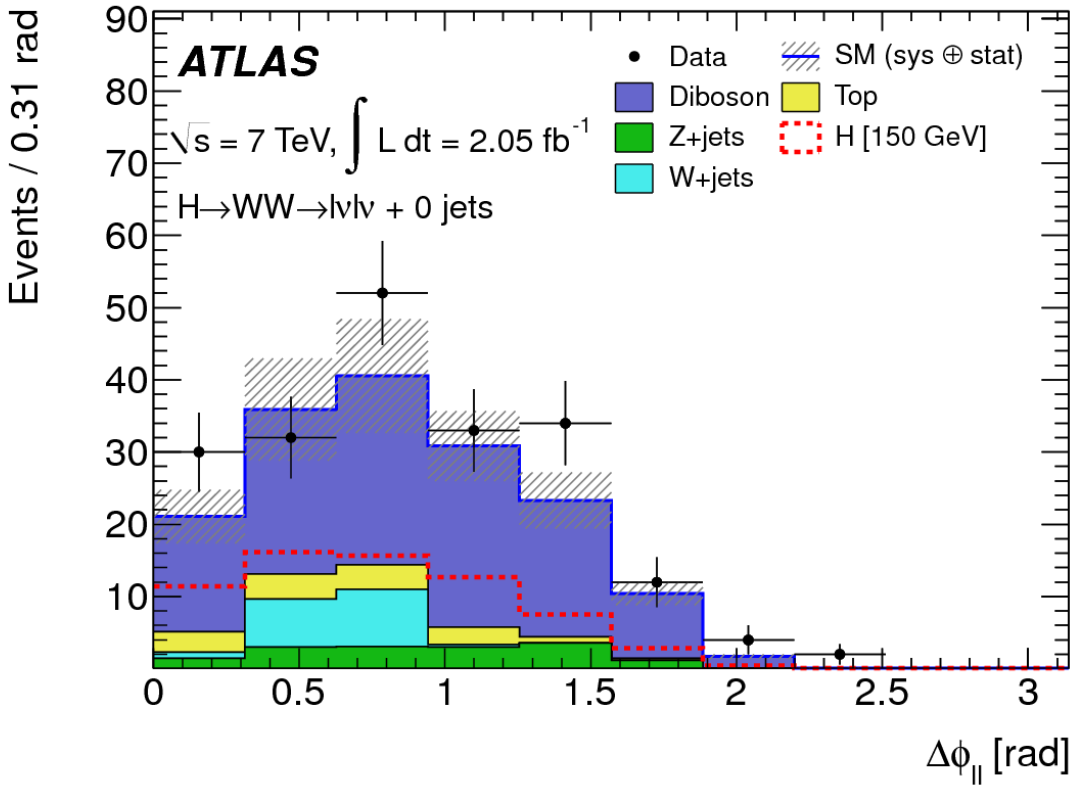




H-> WW analysis

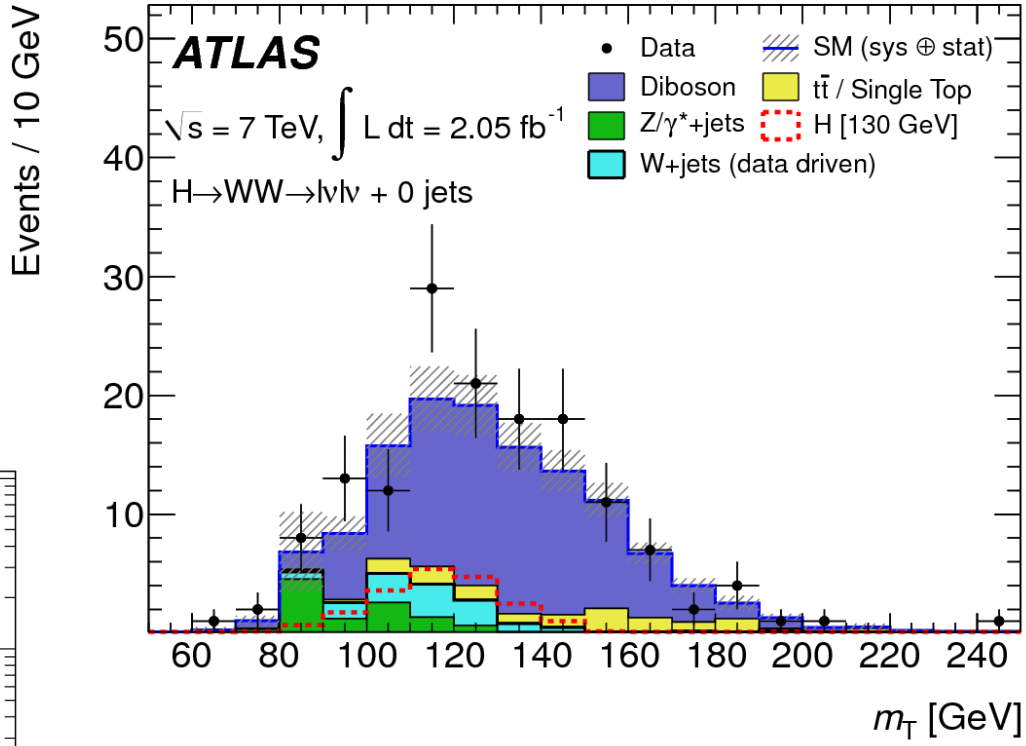
arXiv: 1112.2577 (submitted to PRL)

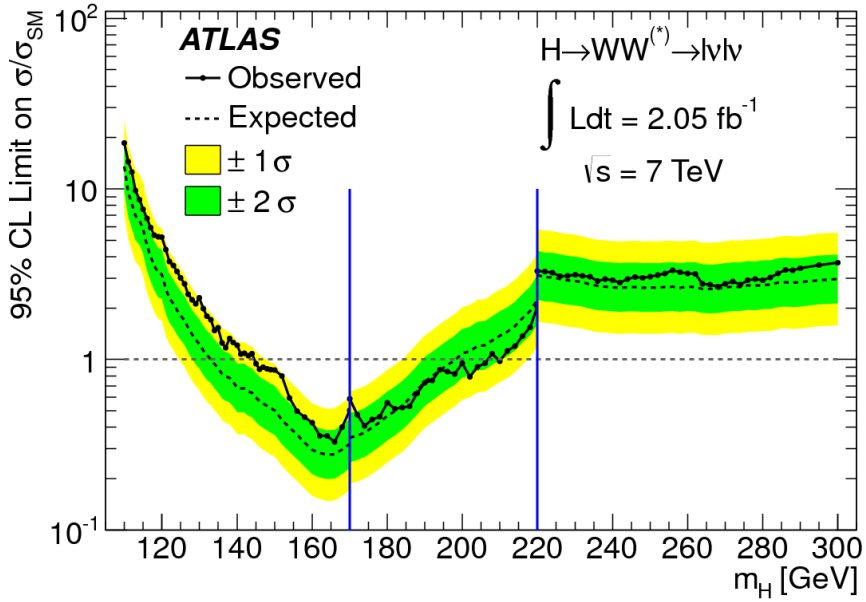
- 2 leptons:
  - $p_T^1 > 20$ or 25 GeV
  - $p_T^2 > 15$ GeV
- Large E_T^{miss}:
  - ee,μμ: >40 GeV
  - eμ: >25 GeV
- Small opening angle between leptons
  - m(ll)<50 GeV
  - p_T(ll)>30 GeV
  - Δφ(ll)<1.8 rad
- Separate by jet count:
  - 0 jets: no jet with p_T>25 GeV
  - 1 jet: exactly one (non-b) jet with p_T > 25 GeV



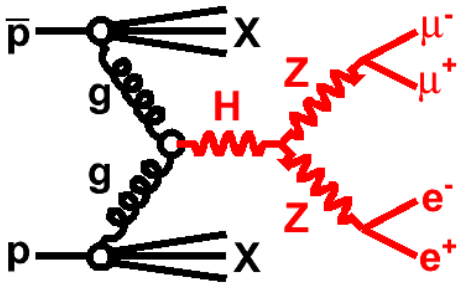
Results

- Final discriminant is transverse mass of leptons and E_T^{miss}
- Data agree with background expectation



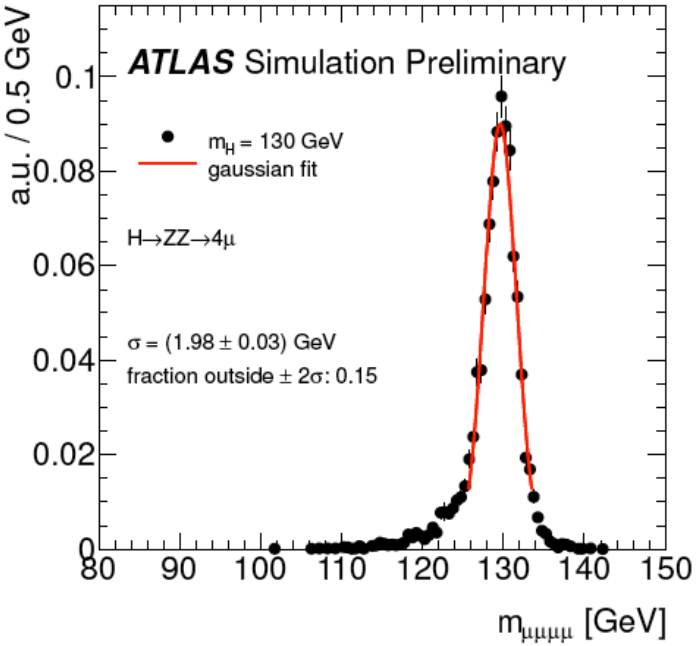


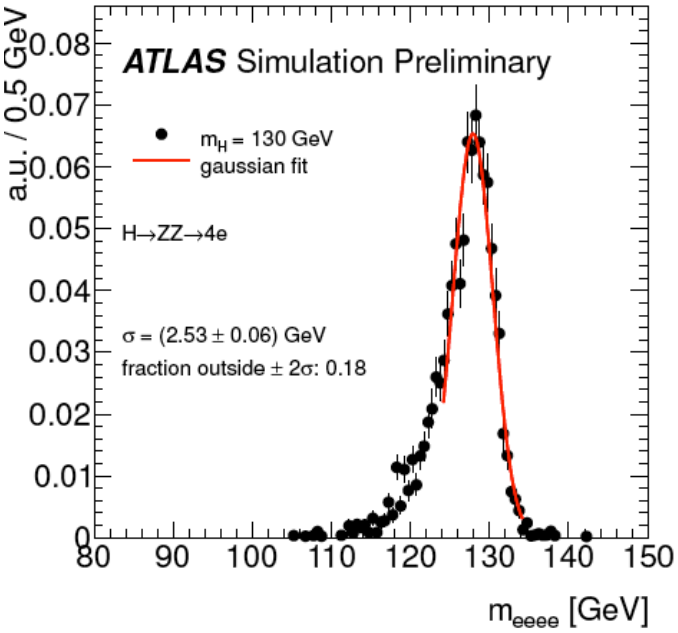
Exclude $145<m_H<206$ GeV at 95% CL
(expected exclusion: $134<m_H<200$ GeV



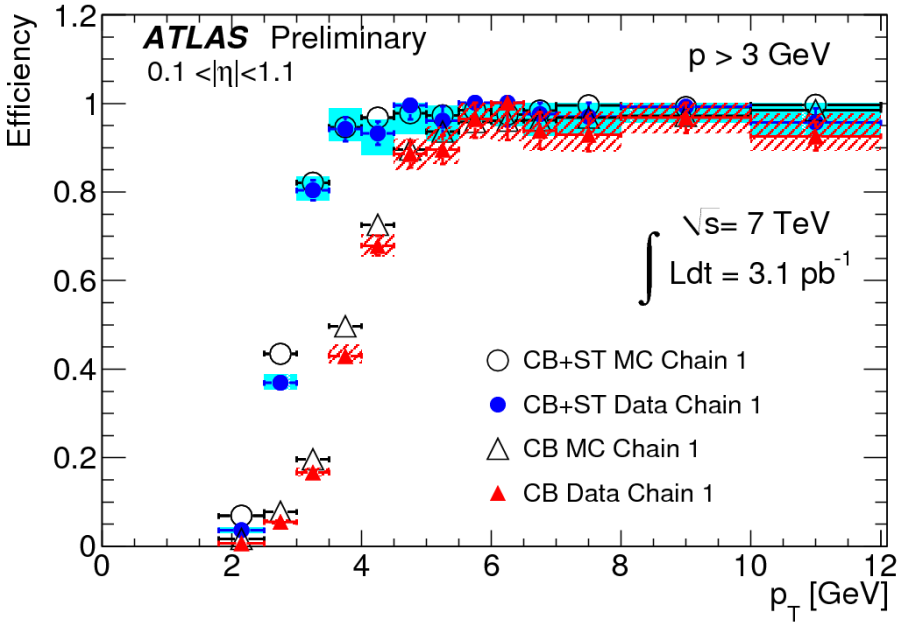
H->Z*Z->4 leptons

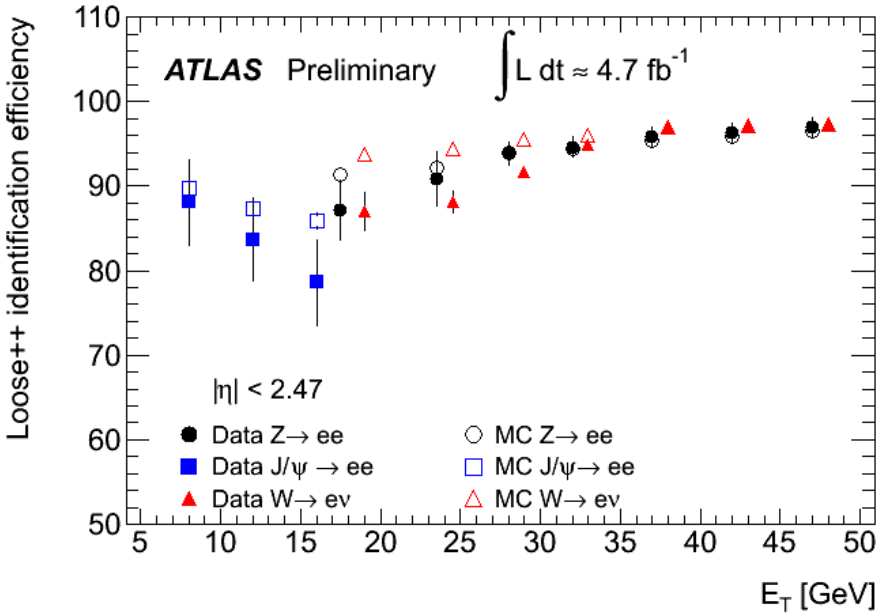
- Rate: σ x BR≈2.8 fb => 15 evts/5 fb^{-1}
- Selection:
  - 4 leptons with p_T>7 GeV
    - 2 leptons with p_T>20 GeV
  - Leading dilepton mass:
    - $|m_{12} - m_Z| < 15$ GeV
  - Subleading mass from off-shell Z boson at low mass: m_{34}>15 GeV
  - 4-lepton mass resolution:
    - Muons: 2 GeV
    - Electrons: 2.5 GeV





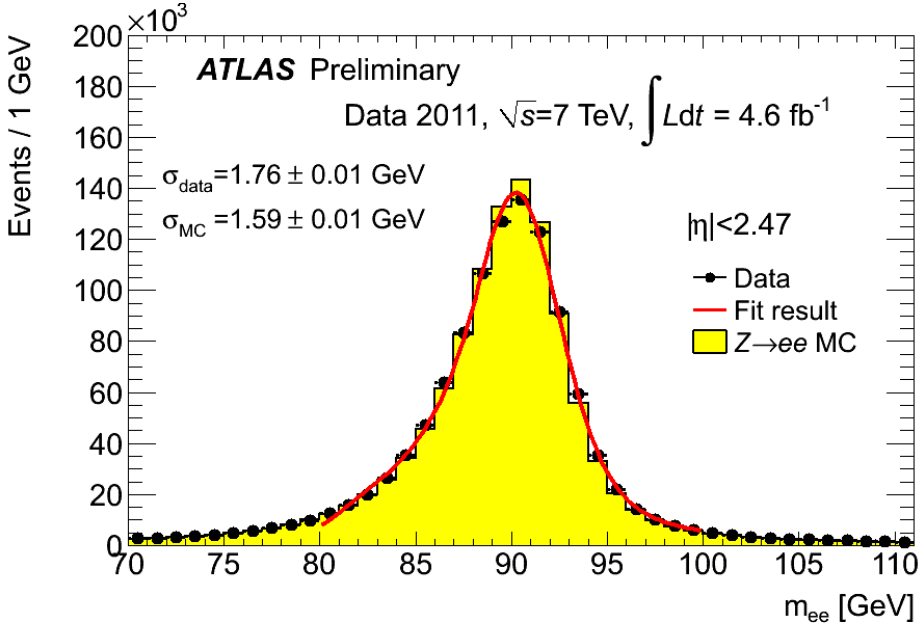
Electron and Muon Efficiencies

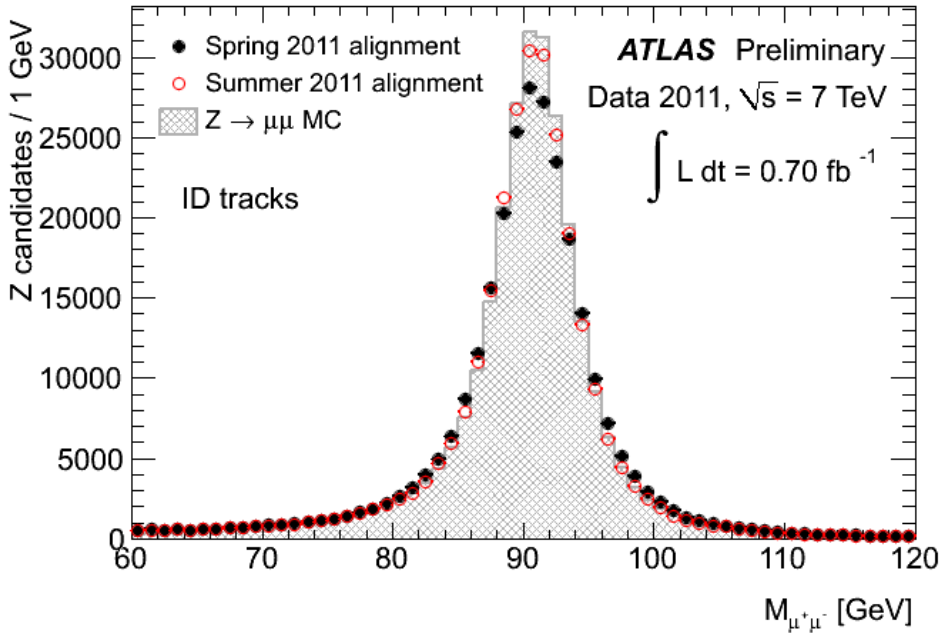




- Muon and electron identification efficiencies measured
  - With J/Psi mesons, Z bosons and W bosons
- Good agreement between data and simulation
  - Disagreements are corrected for
  - Residual effects folded into systematic uncertainty

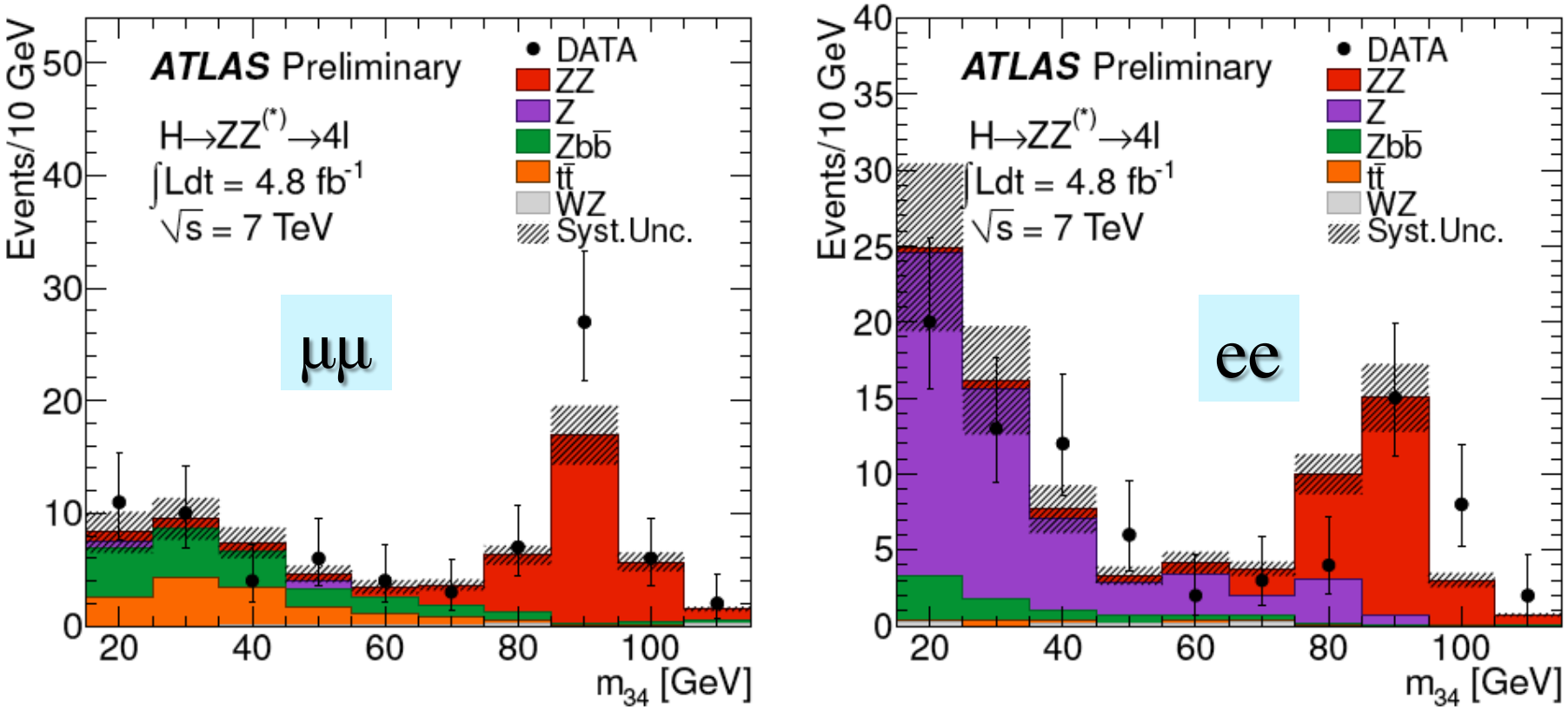
Electron energy and Muon Momentum Measurement





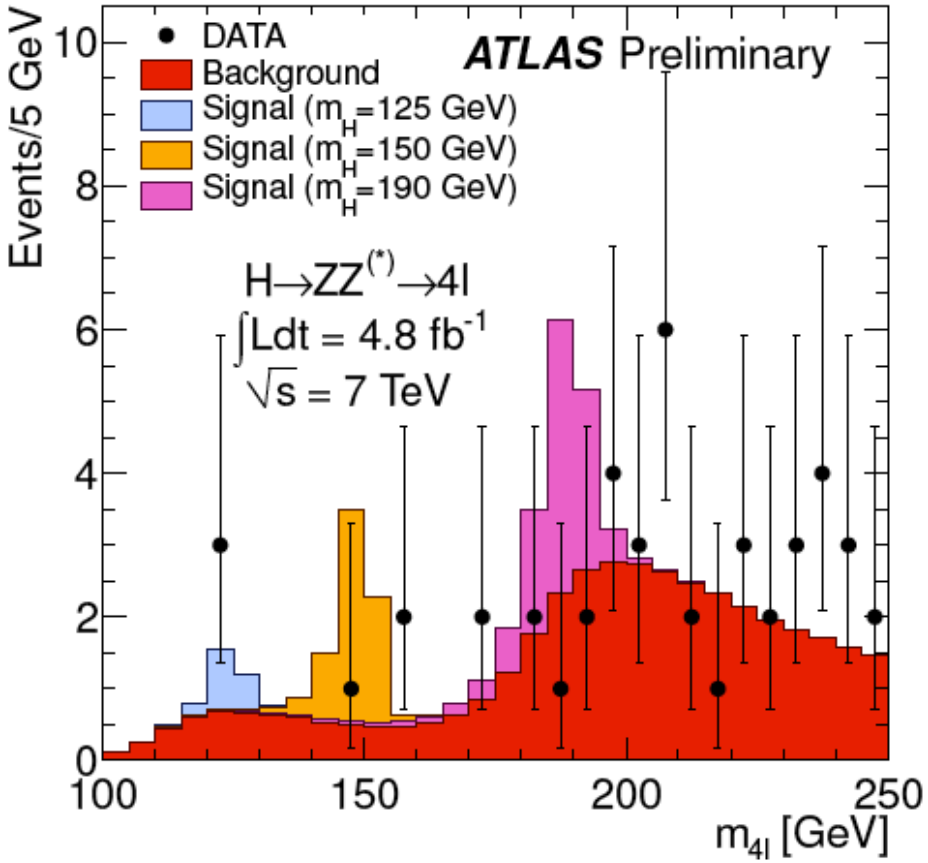
- Recent reprocessing of data resulted in improved calibrations:
  - EM calorimeter:
    - constant term 1.0% (barrel) - 1.7% (endcap)
  - Tracker:
    - Expected intrinsic resolution: 2.05 GeV
    - Data intrinsic resolution: 2.21 GeV (was 2.69 GeV)

H->ZZ(*) Search: Background Control



- Invariant mass distribution of sub-leading mass in background enriched sample
  - No requirements on isolation, impact parameter and charge of the two leptons
- Data well described by background model

Results of 4-lepton search



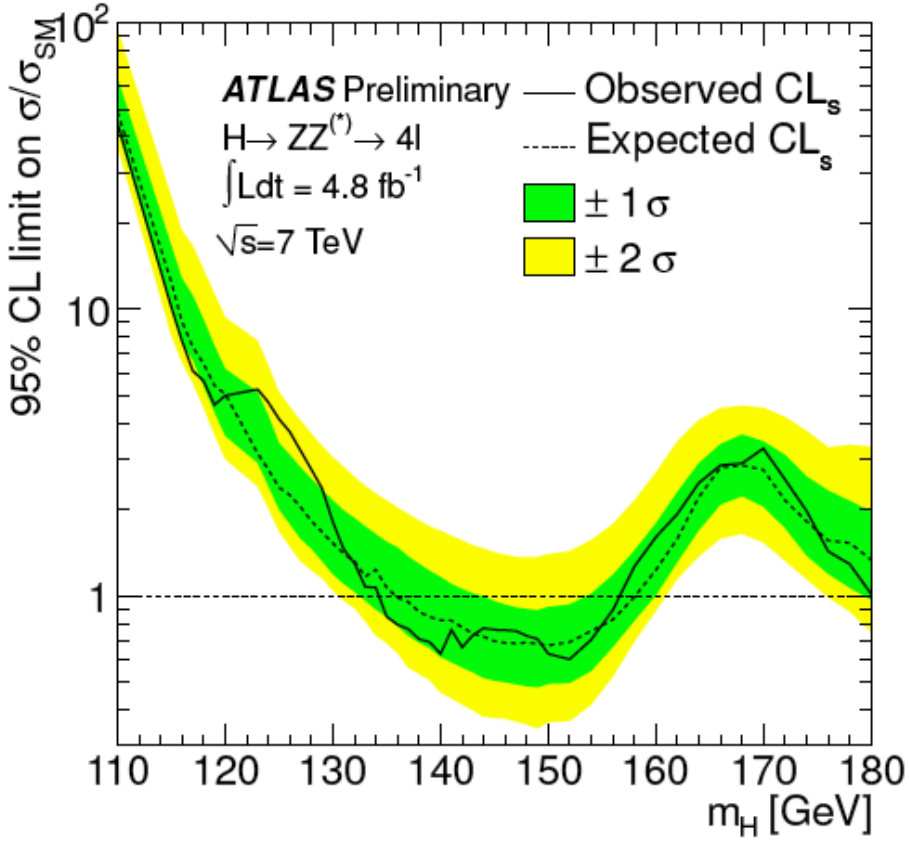
Number of Events with m(4l)<180 GeV

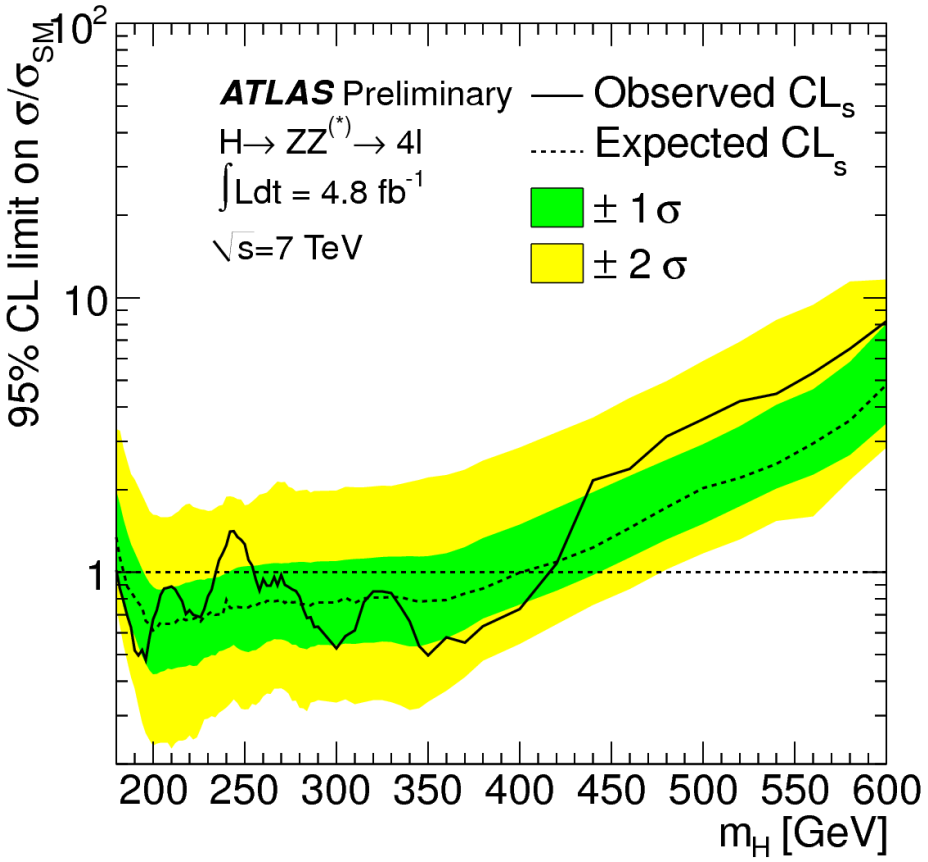
	Data	Background
eeee	2	2.9±0.8
eeμμ	3	4.2±0.8
μμμμ	3	2.2±0.3

High Purity: Signal/Background ~1

- In the region m_H<140 GeV (not already excluded previously) 3 events are observed at very similar mass values
  - Two eeμμ events at m(4l)=124.3 and 123.6 GeV
  - One 4μ event at m(4l)=124.6 GeV

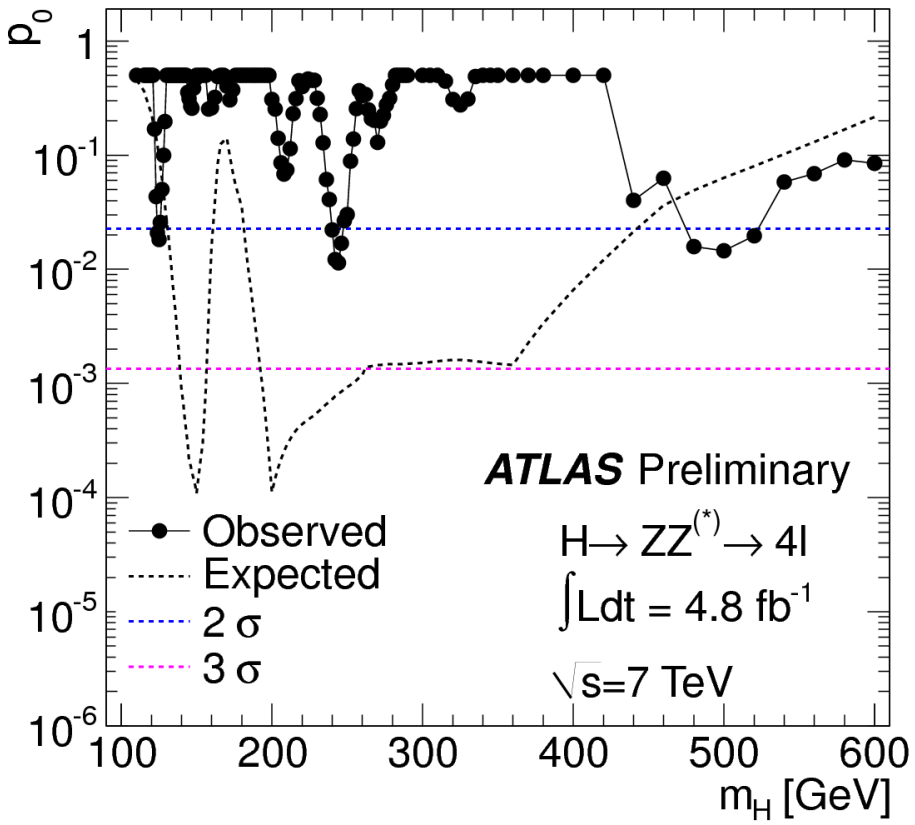
Interpretation of H->4 lepton Search





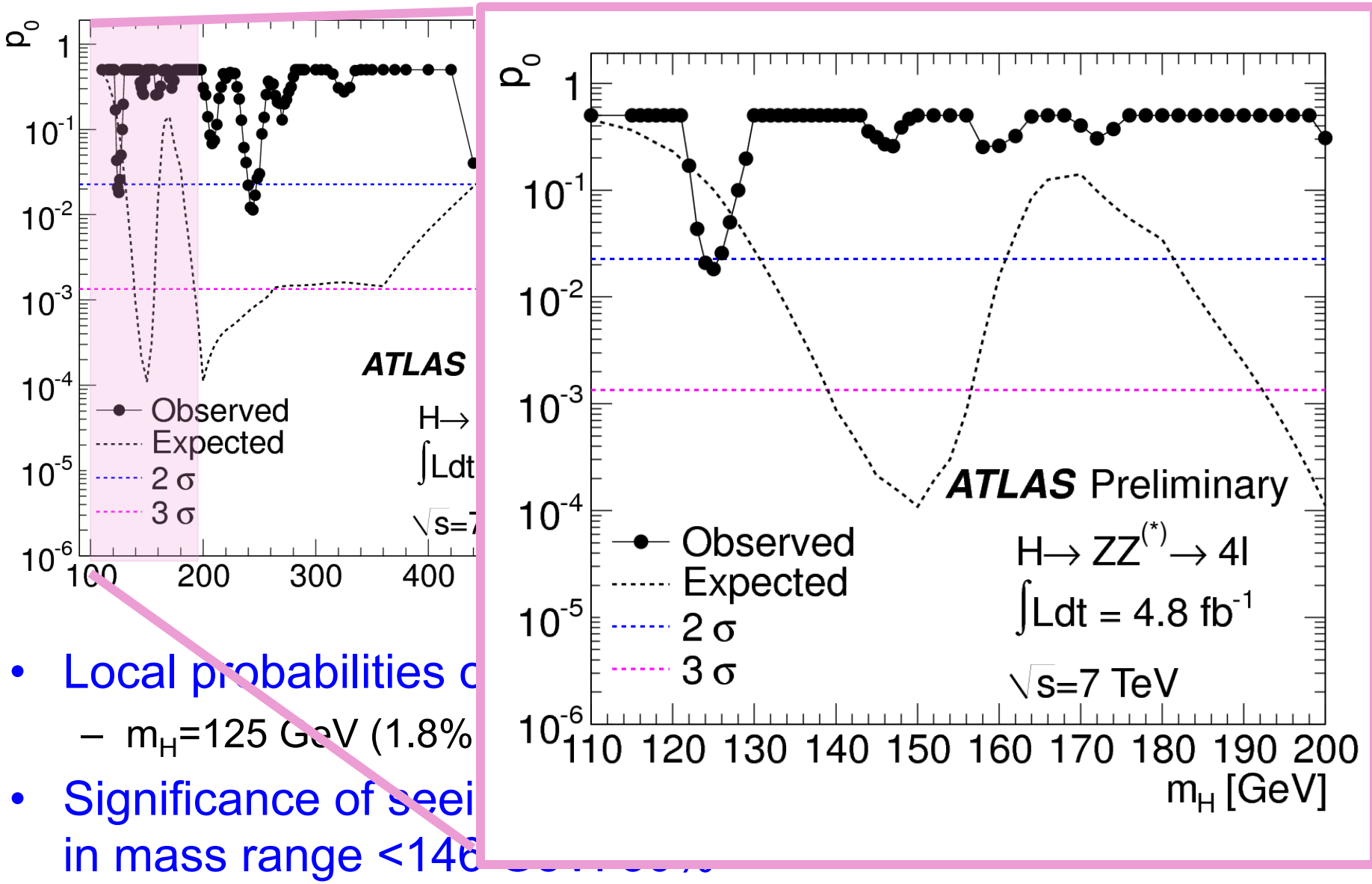
- Observed limit agrees with expected limit to within 2σ over full mass range

Interpretation of H->4 lepton Search



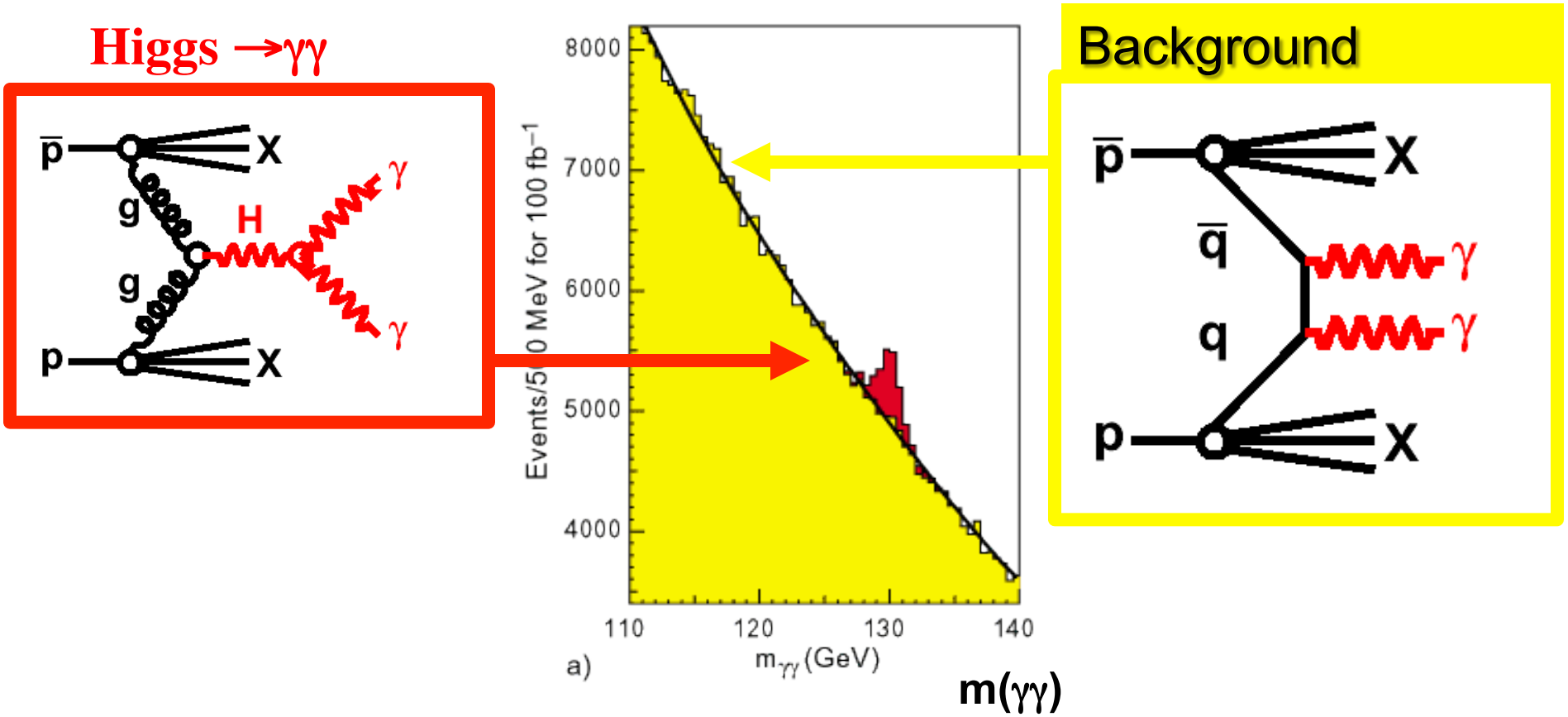
- Local probabilities of three most significant excesses:
  - m_H=125 GeV (1.8%), m_H=244 GeV (1.1%), m_H=500 GeV (1.4%)
- Significance of seeing at least one excess with p-value of 1.8% in mass range <146 GeV: 30%

Interpretation of H->4 lepton Search



- Local probabilities c
  - m_H=125 GeV (1.8%
- Significance of seei
  in mass range <14

Higgs decaying to two photons

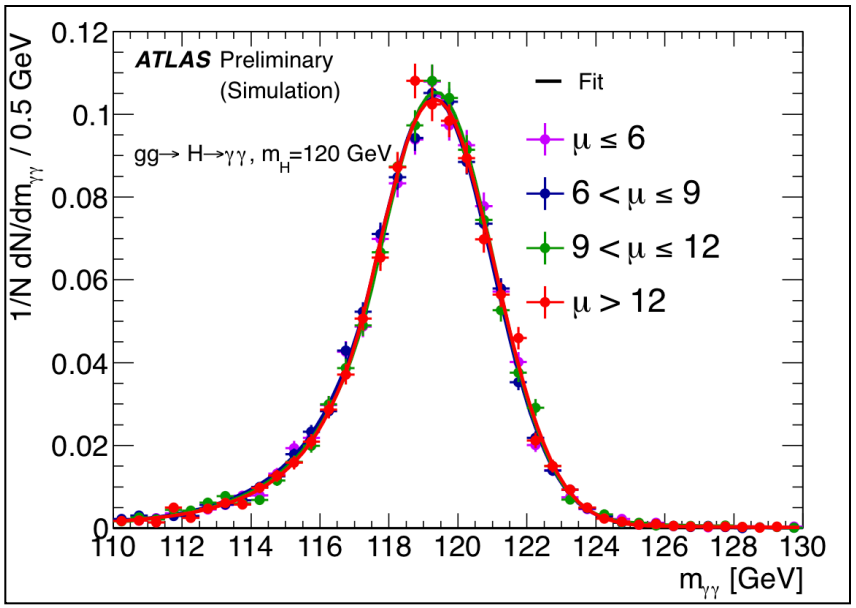


- σ x BR=43 fb => 215 evts/5fb^{-1} for m_H=120 GeV
  - 70 events expected after reconstruction and event selection
- But large background from prompt diphoton events and from jets with leading π^0's
  - Signal/Background ~3% (~70/2300)

Energy Scale and Resolution

$$m^2_{\gamma\gamma} = 2\, E_1\, E_2\, (1-\cos\alpha)$$

Mass resolution (m_H=120 GeV)		
category	**σ(m) [GeV]**	**Fraction in core (±1.4σ)**
all	1.7	80%
Best category (unconverted barrel)	1.4	84%
Worst category	2.3	70%



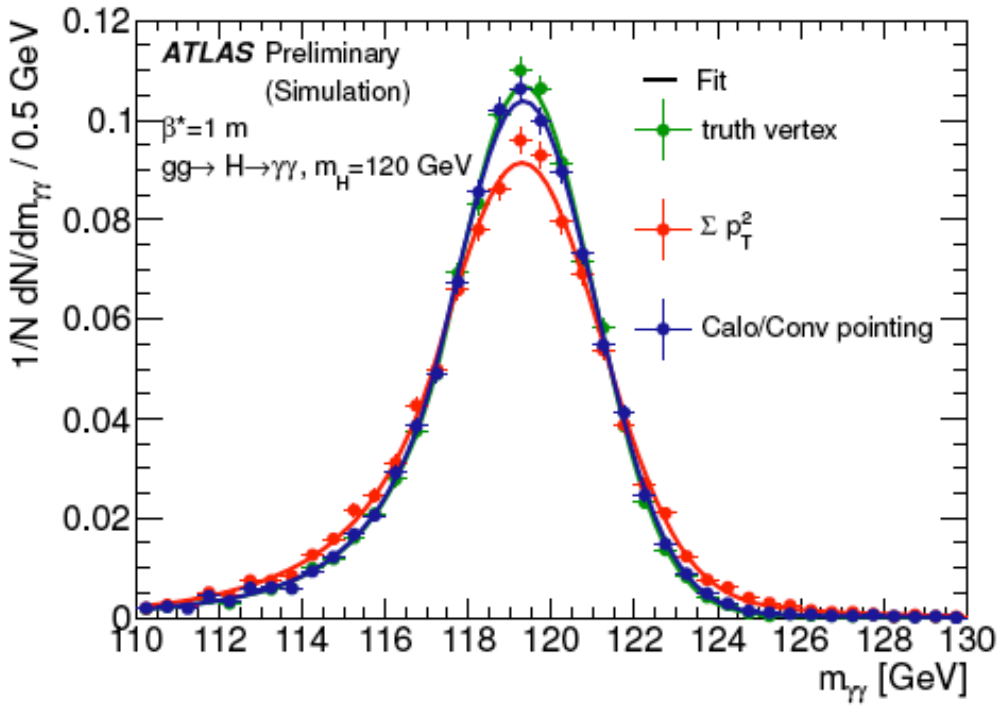
- **Energy scale at m(Z) known to ±0.5%**
- **Linearity better than ±1%**
  - **from few GeV to few 100 GeV**
- **Intercalibration: 1% (barrel) to 1.7% (endcap)**
- **Pileup has no impact on mass resolution**

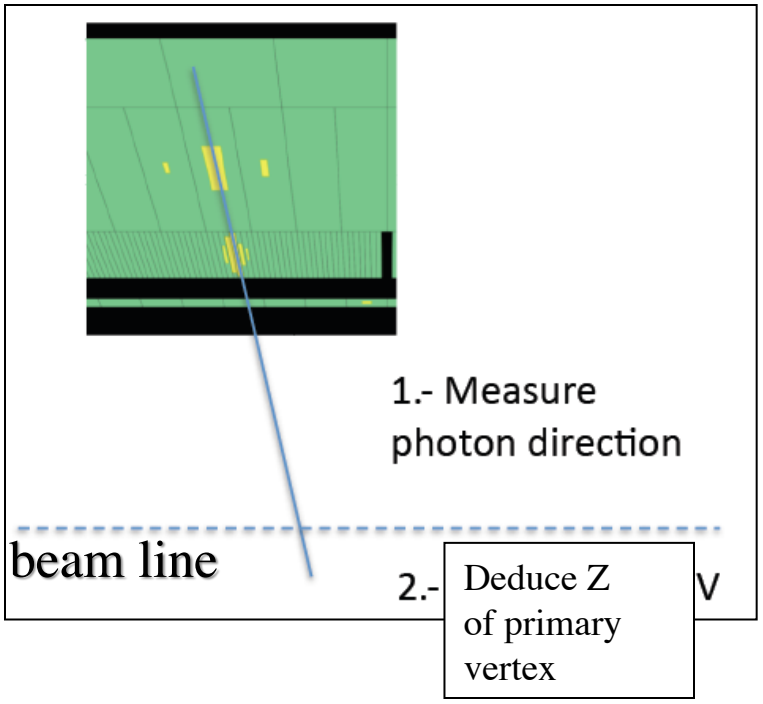
Photon Angle Determination

- Use calorimetric polar angle measurement to determine correct vertex
  - Due to high pileup z-vertex belonging to hard interaction cannot be uniquely identified

$$m^2_{\gamma\gamma} = 2\, E_1\, E_2\, (1-\cos\alpha)$$

α = opening angle between γ's

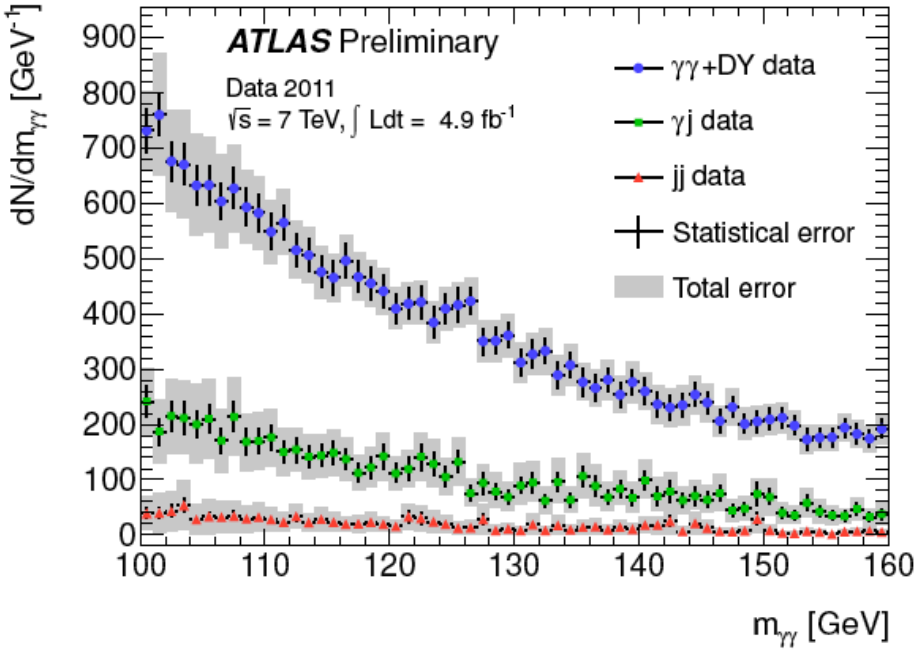


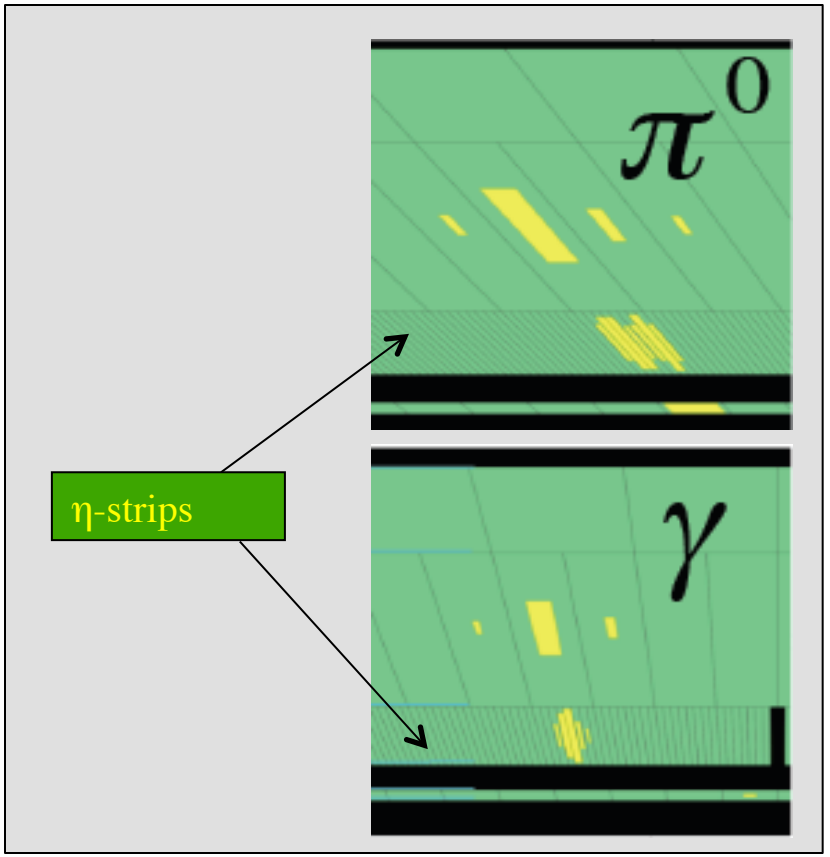


- Validated with Z->ee events
- Angular term to mass resolution now negligible

Rejection of π^0->$\gamma\gamma$ Background

- Fine segmentation of strip layer in LAr calorimeter in η-direction
  - Designed to reject precisely this background
  - Also used to estimate background composition

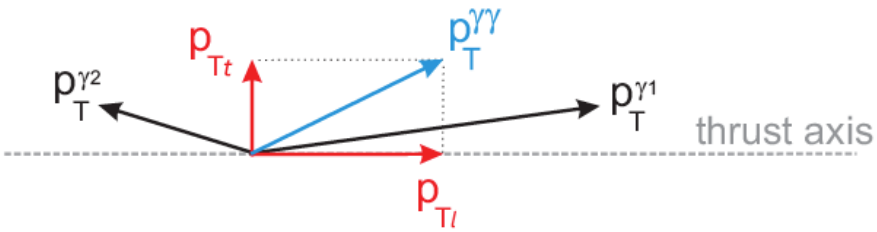




- **71 ± 5 % of background from irreducible prompt diphoton production**

Analysis Strategy

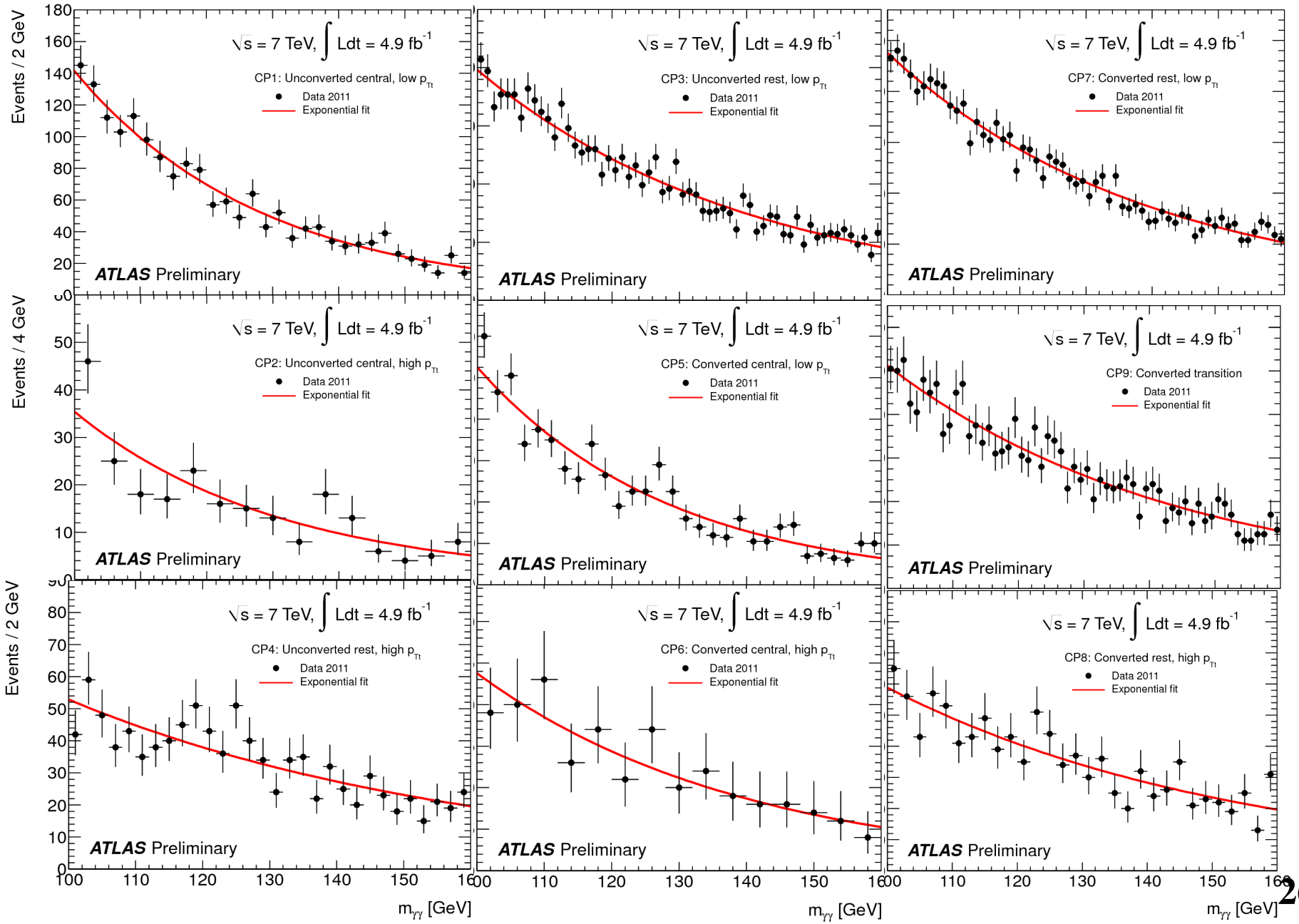
- Events with two isolated photon candidates selected:
  - **$E_T(\gamma_1)$>40 GeV**
  - **$E_T(\gamma_2)$>25 GeV**
- Isolation cut:
  - **E_T<5 GeV in 0.4 cone around photon**
- Divide sample into 9 categories:
  - Converted versus unconverted
  - High $p_T(\gamma\gamma)$ versus low $p_T(\gamma\gamma)$
  - Different η regions



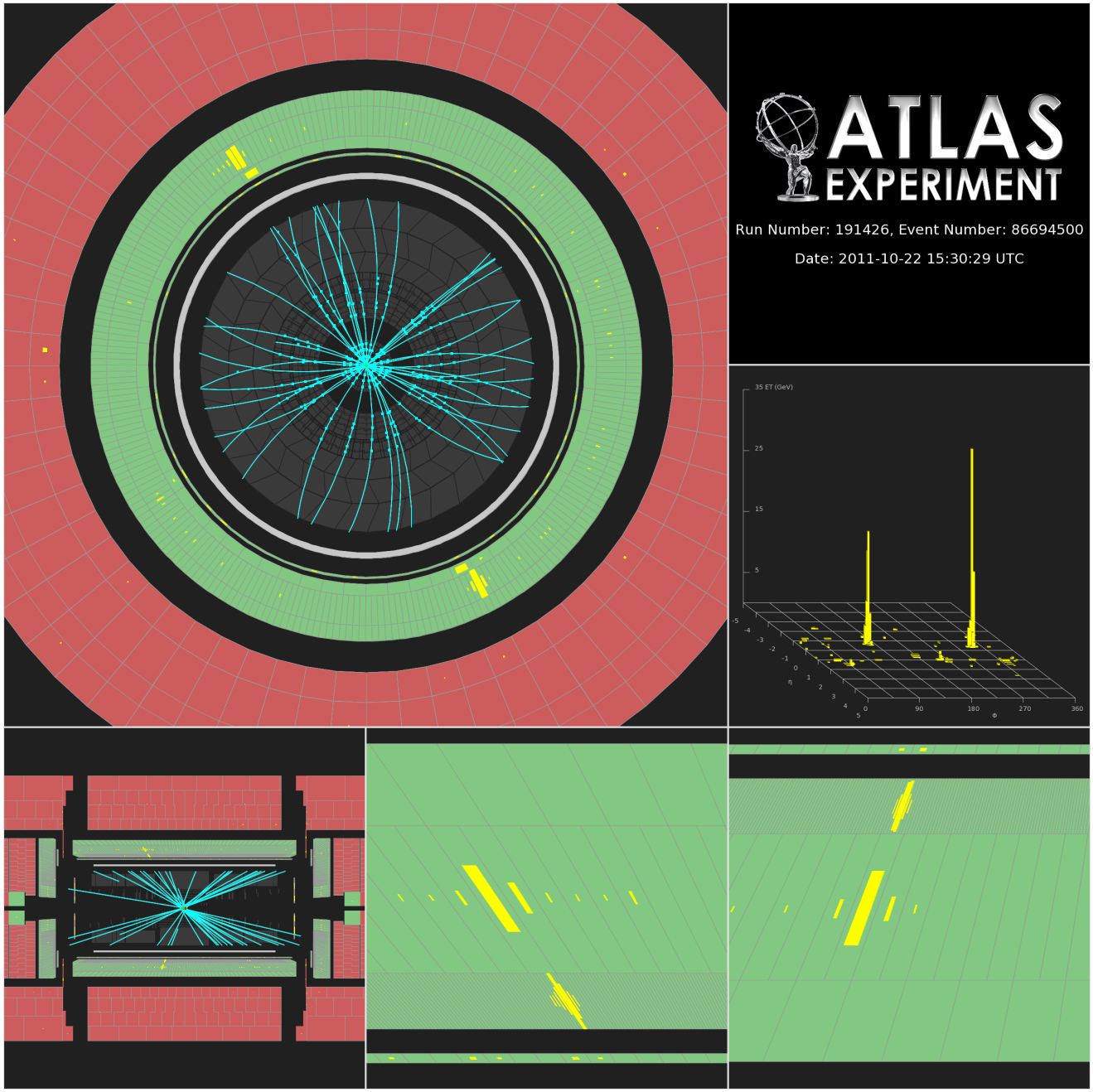
Examples of categories

category	FWHM (GeV)	Signal	S/BG
Unc. low pt central	3.4	7.3	0.051
Unc high pt central	3.3	3.3	0.117
Conv. Low pt central	3.9	4.7	0.038
Conv. transition	5.8	5.9	0.014
Unc. Low pt other	4.1	13.5	0.023
Conv. Low pt other	4.7	14.0	0.017

Diphoton Mass Spectra by Category



A Diphoton Event at m(γγ)=126 GeV



Category: unconverted barrel

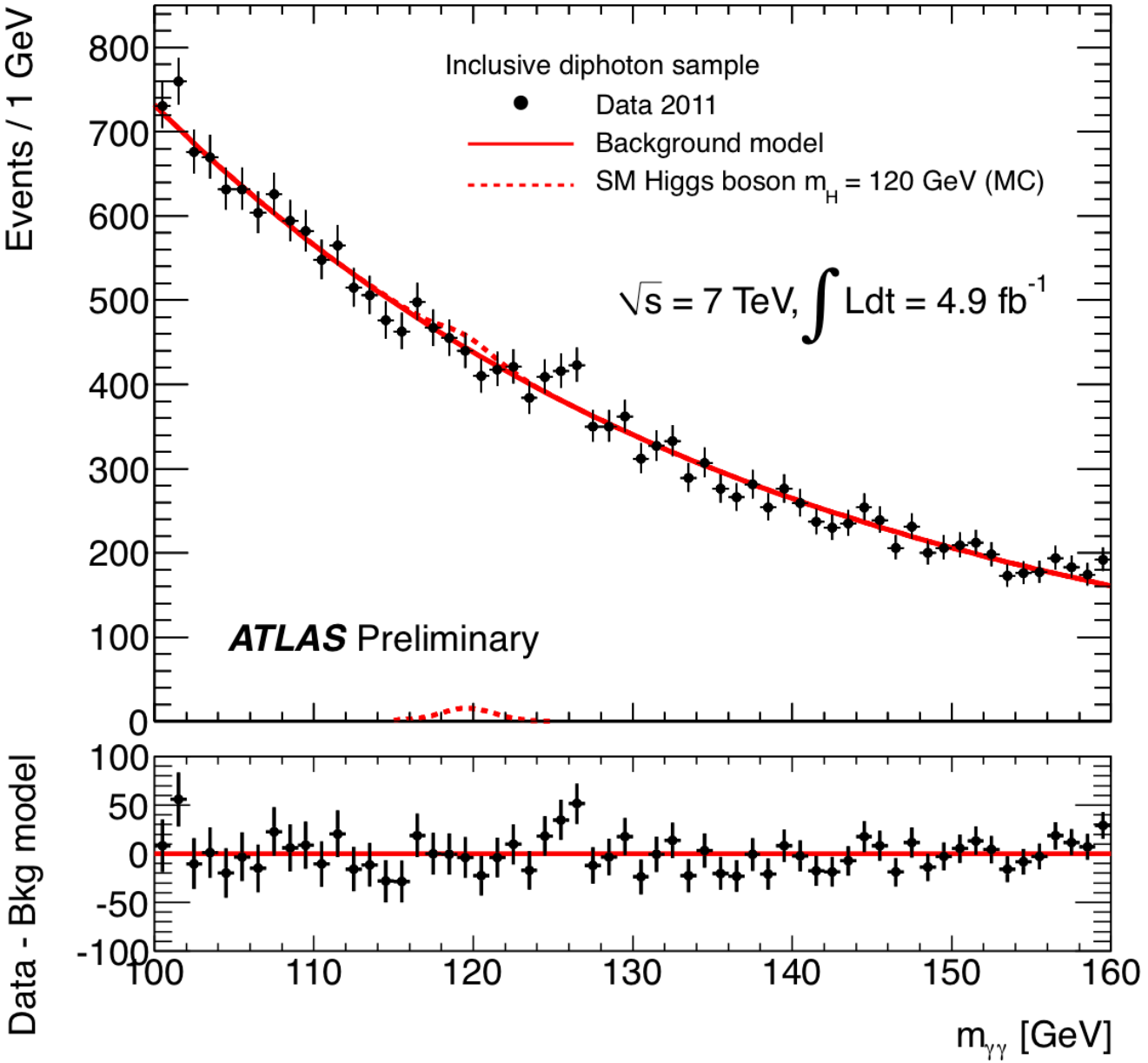
Background Shape

- Use single exponential fit for each of the 9 categories
  - Systematic uncertainty assigned for each background category using prompt diphoton MC (DIPHOX and RESBOS): 0.1 - 5.6 events

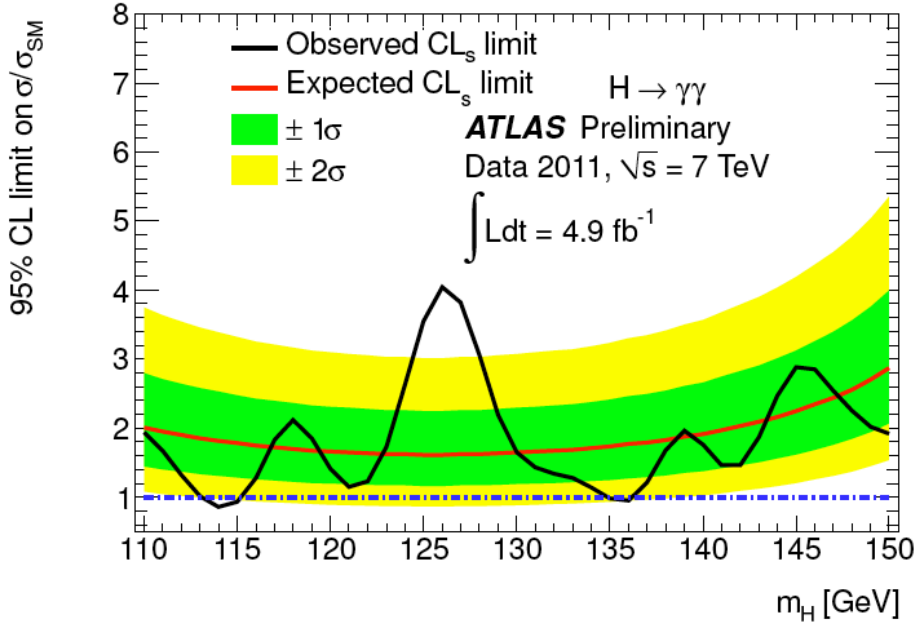
Category	CP1	CP2	CP3	CP4	CP5	CP6	CP7	CP8	CP9
Events	±4.3	±0.2	±3.7	±0.5	±3.2	±0.1	±5.6	±0.6	±2.3

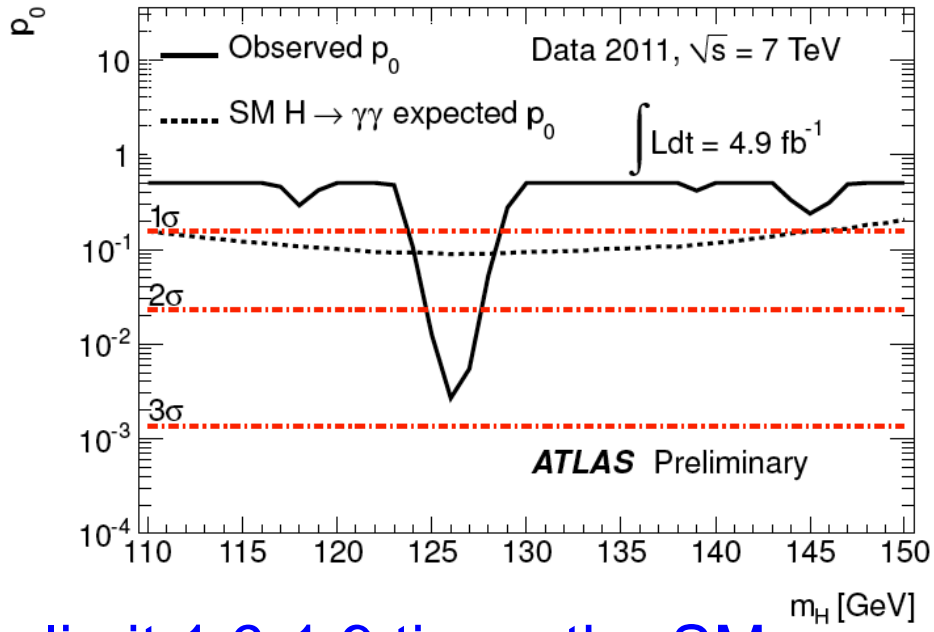
- Many robustness tests: local significance of largest excess stable to within 0.16 σ
  - E.g. alternative fit functions
  - Double background model uncertainties
  - Introduce extra uncertainty on resolution

Overall Diphoton Mass Distribution



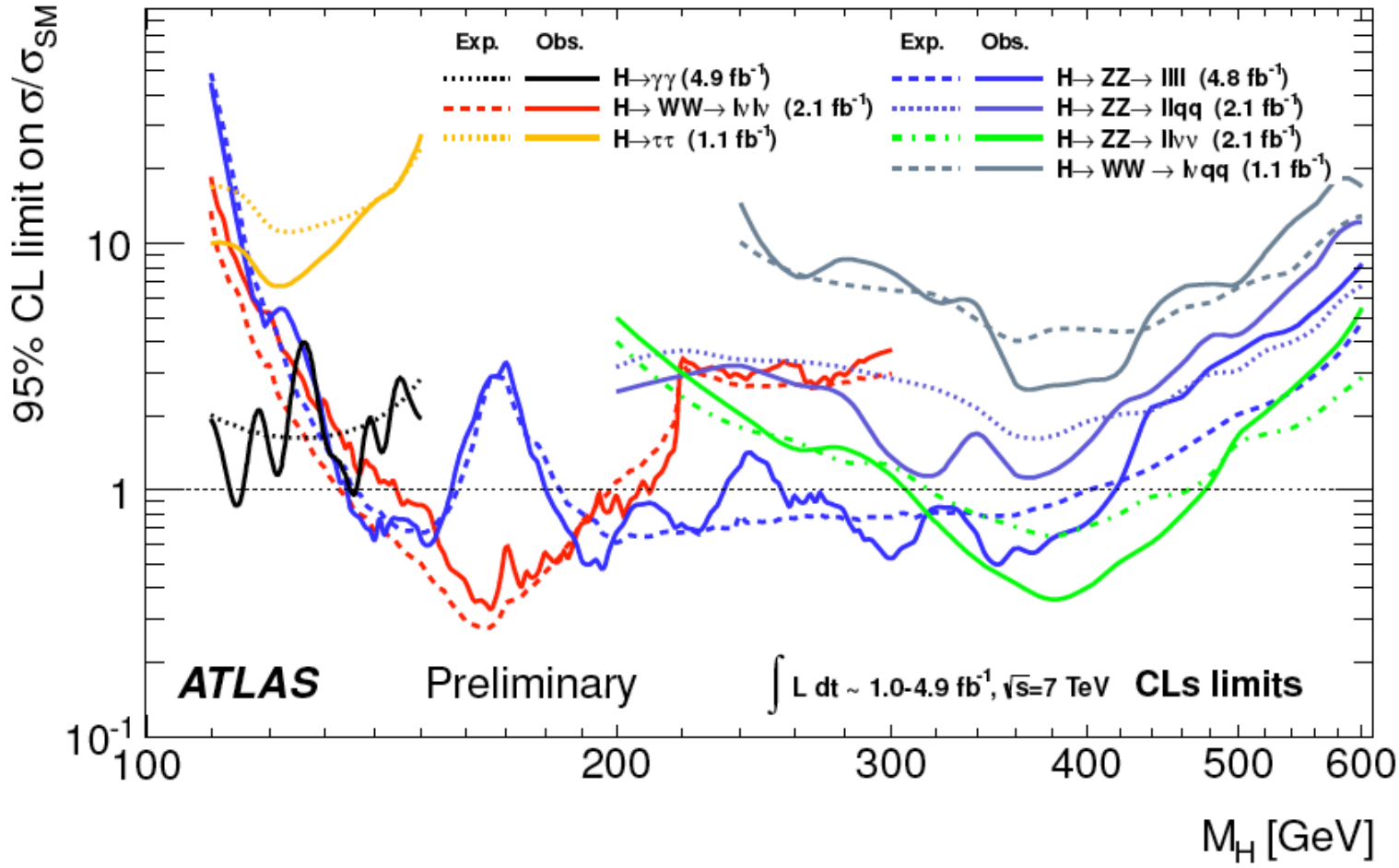
H->γγ Cross Section Limit





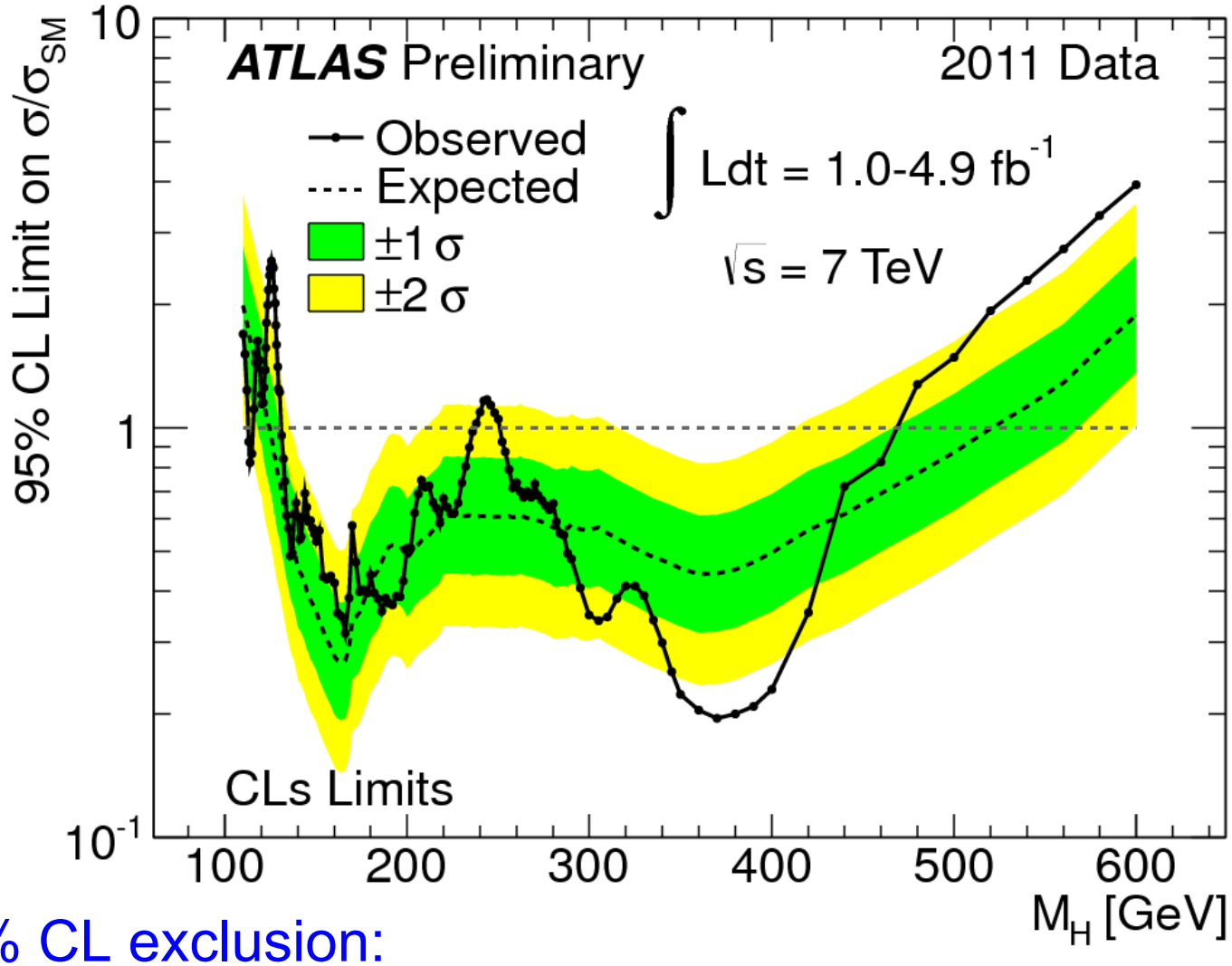
- Expected 95% CL cross section limit 1.6-1.9 times the SM value for m_H<140 GeV
- Observed 95% CL limit excludes 114<m_H<115 GeV and 135<m_H<136 GeV
- Most significant excess occurs at m_H=126 GeV and has local probability of background fluctuation of p_0=0.27%
  - Probability that such a fluctuation occurs *anywhere* in distribution: 7%

Combining ATLAS Higgs Constraints



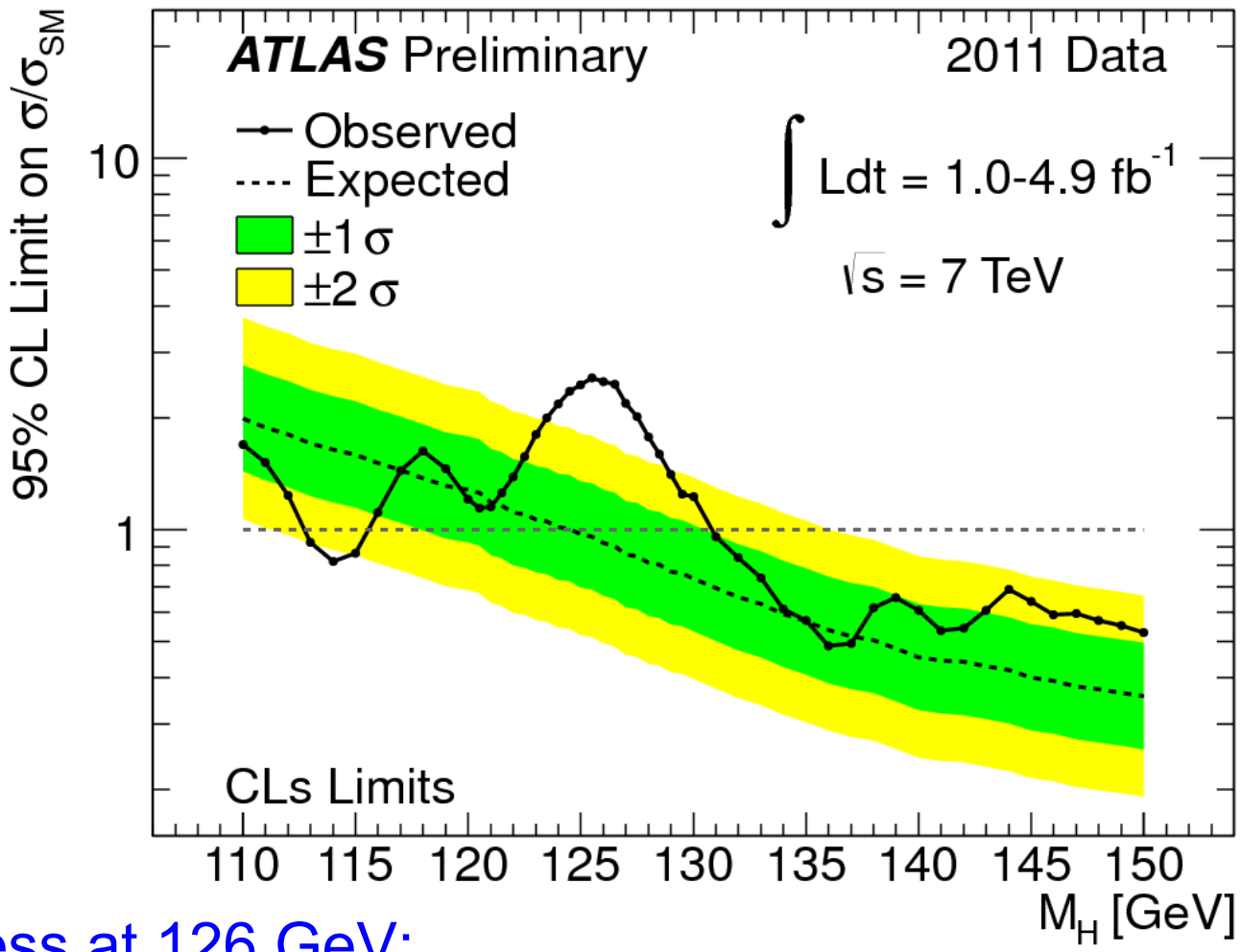
- Combination includes careful treatment of all systematic uncertainties and their correlations

Combined ATLAS Higgs Constraints



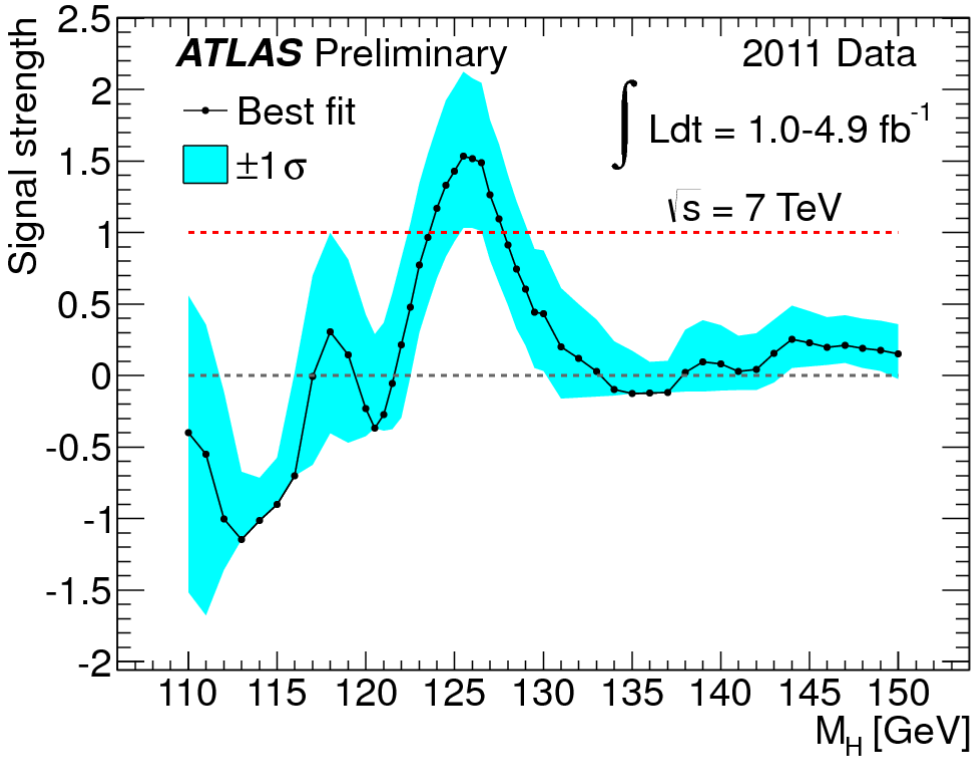
- 95% CL exclusion:
  - Expected: 124.6<m_H<520 GeV
  - Observed: m_H<115, m_H=131-237 and m_H=251-453 GeV

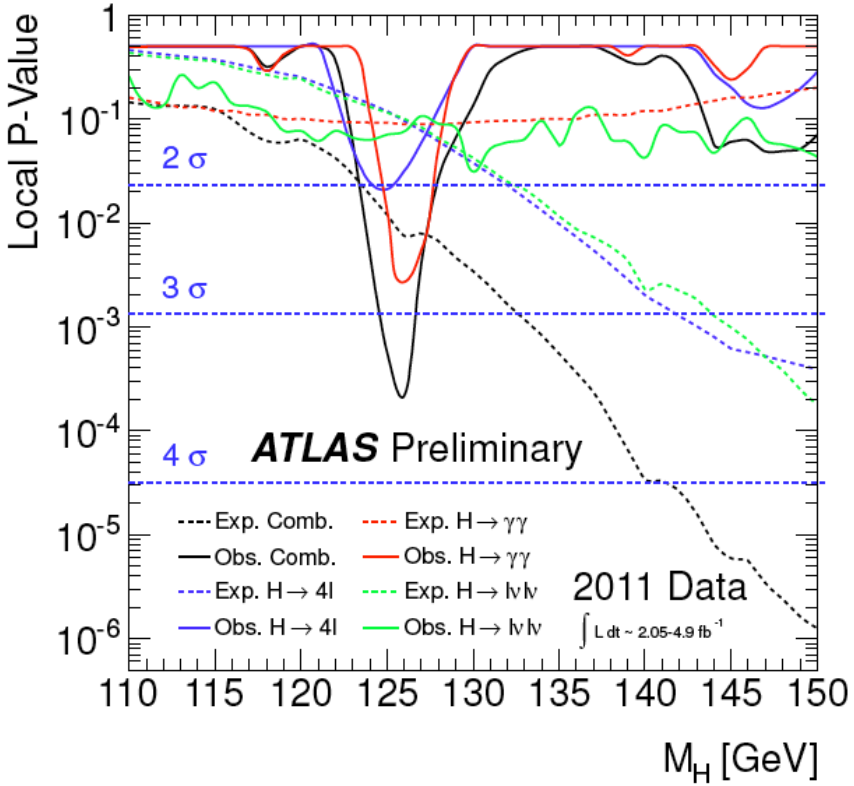
Low Mass Region



- Excess at 126 GeV:
  - local significance: 1.9×10^{-4} (3.6 σ)
  - Global significane: 0.6-1.4% depending on choice of mass range (<146 GeV or full range)

Would this be compatible with a SM Higgs at m_H~126 GeV?





- Strength of excess at 126 GeV corresponds to 1.5±0.5 times the SM cross section
  - Consistent with SM Higgs production
- All three sensitive channels contribute:
  - H->γγ: 2.8σ, H->4l: 2.1σ, H->WW: 1.4σ

Conclusions

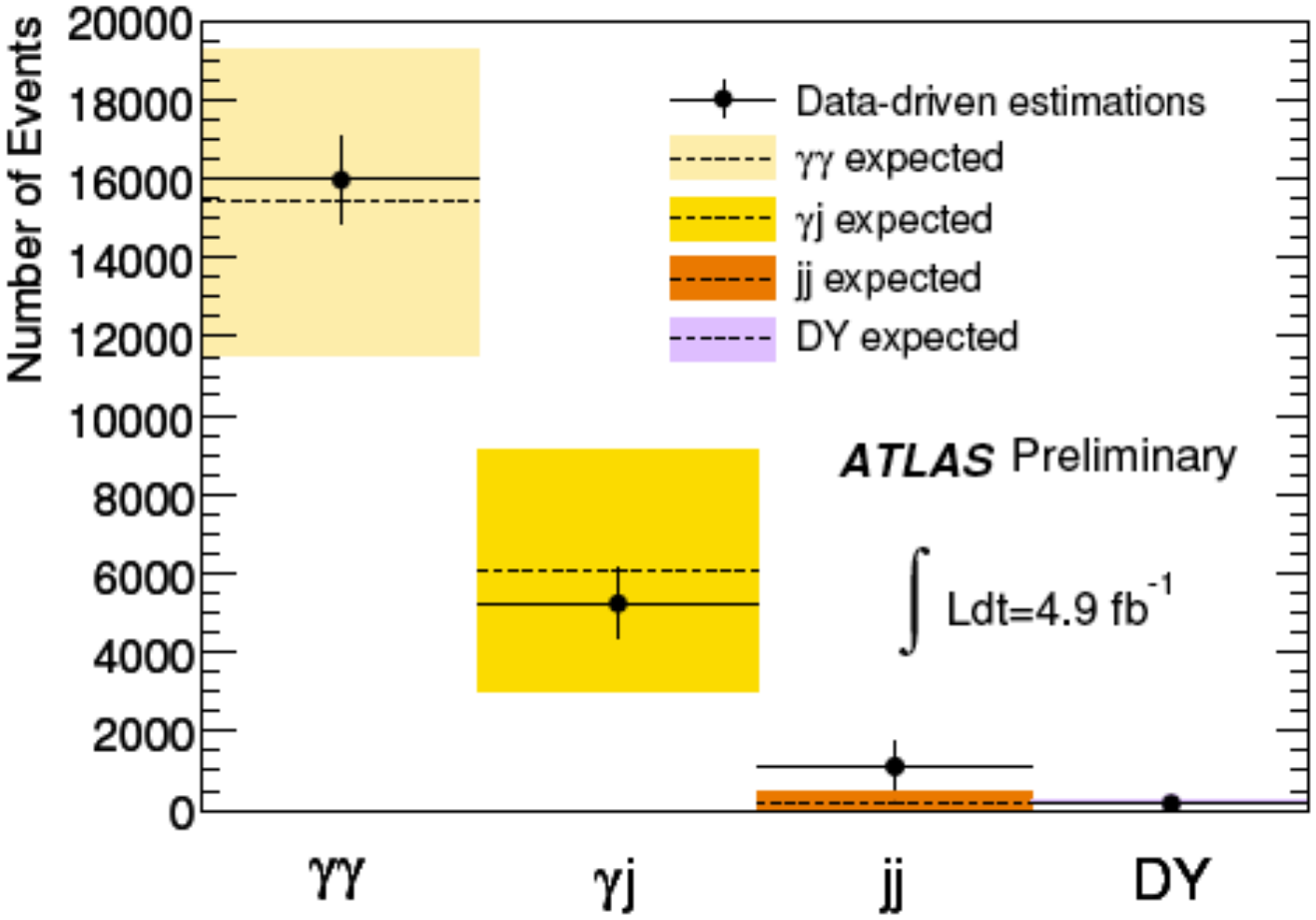
- It has been a fantastic year for the LHC
  - More than 5 fb^{-1} recorded by ATLAS (thanks to LHC!!)
- ATLAS has analyzed full dataset for the most valuable low mass channels
  - Diphoton and 4-lepton decay have excellent sensitivity and allow precise mass reconstruction
- Higgs boson excluded for large region of possible masses
  - Most promising remaining range: $115<m_H<131$ GeV
- Most significant excess observed at $m_H \approx 126$ GeV
  - Global significance (considering look-elsewhere effect) is about 1% (2.3 σ)
- Expect to quadruple dataset in 2012 (15 fb^{-1})
  - Likely with increased $\sqrt{s}$ of 8 TeV
  - This dataset will clarify if the Higgs boson exists (in it's most simple form)

More detailed information

- WW result: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2011-08/
- 4-lepton result: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-162/
- Diphoton result: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-161/
- Combination: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-163/

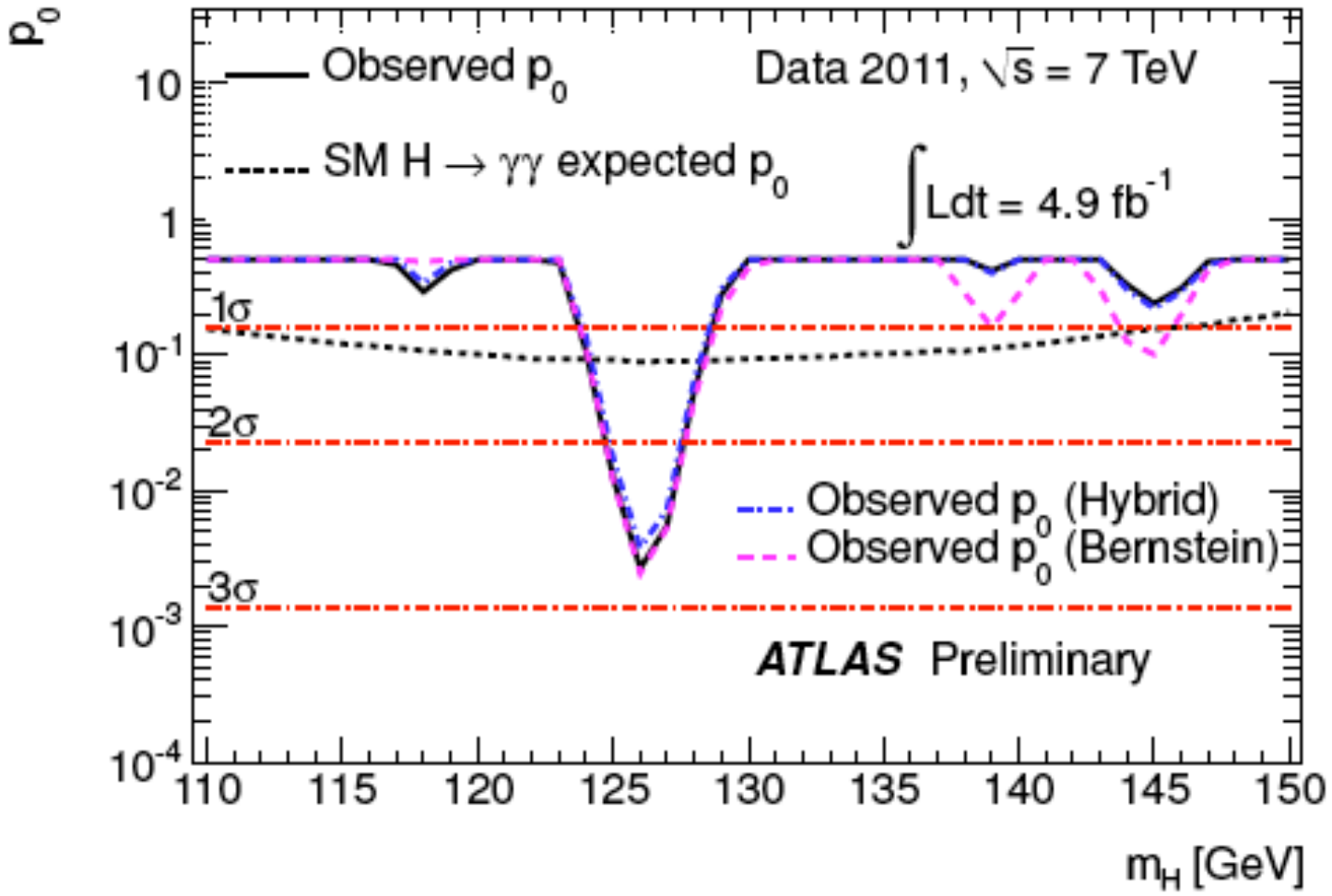
Backup

Background Composition



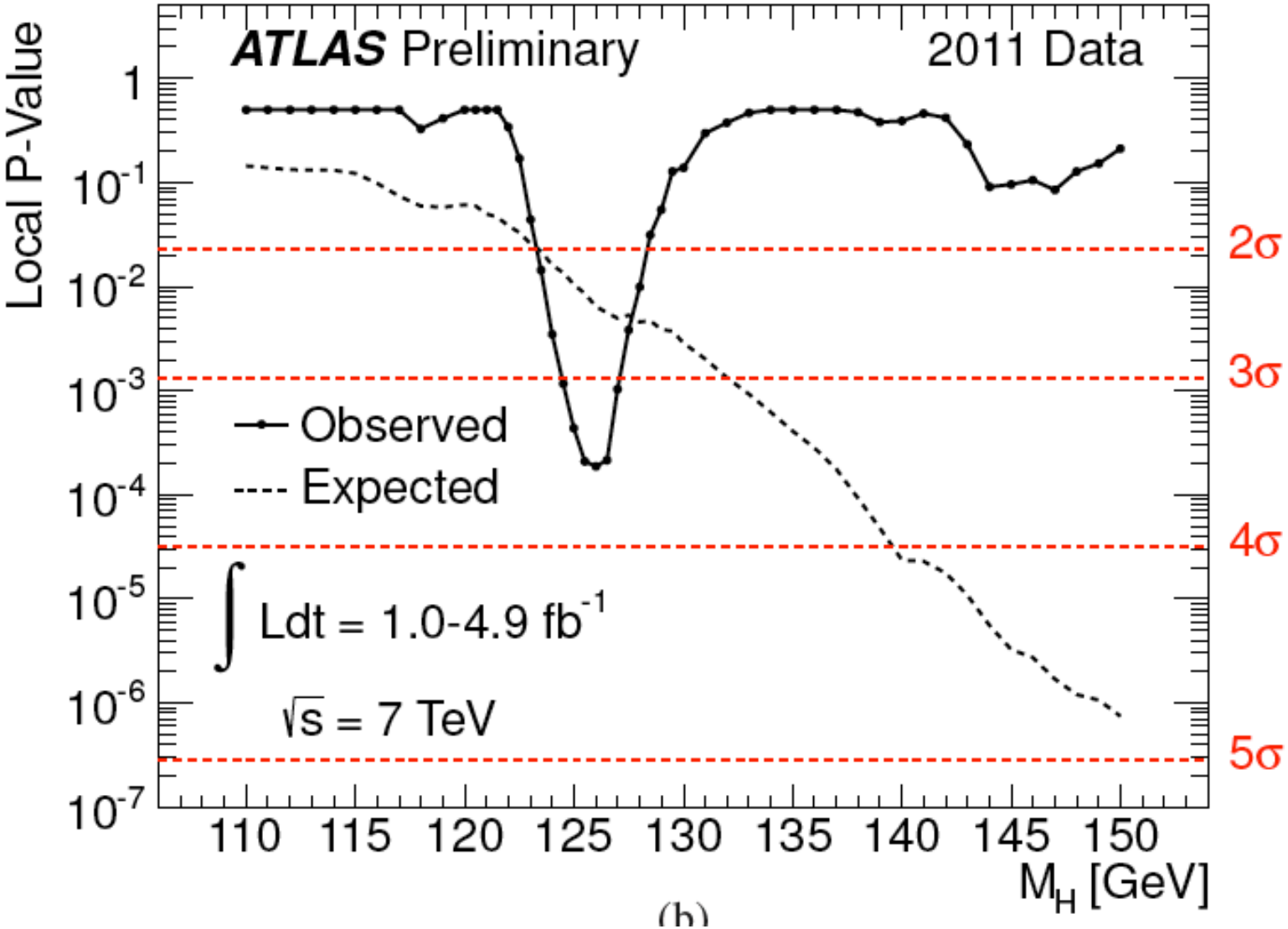
- Observed composition agrees with estimate based on MC

Alternative Background Models

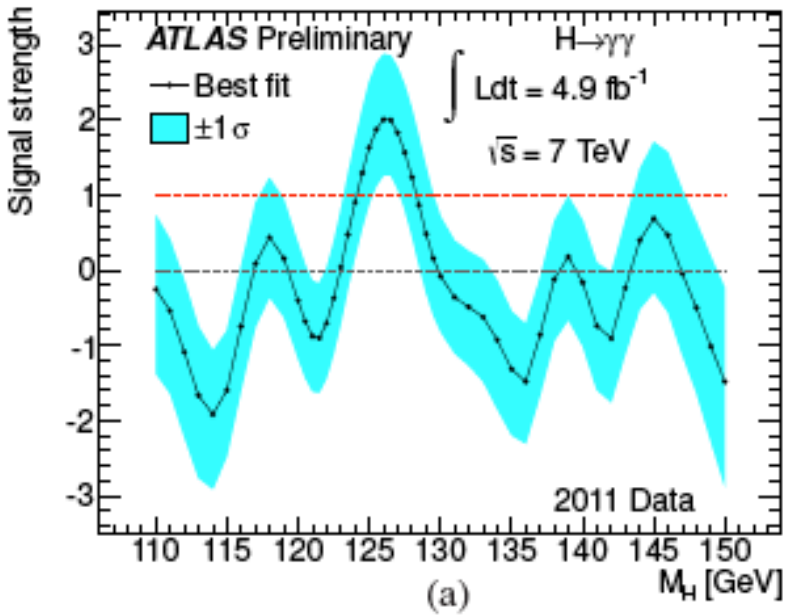


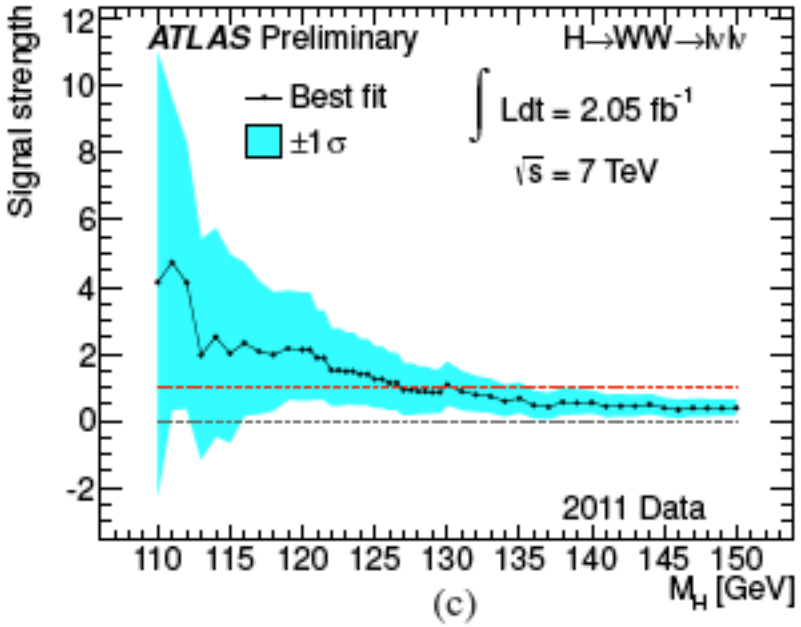
- Local significance nearly identical for different background models

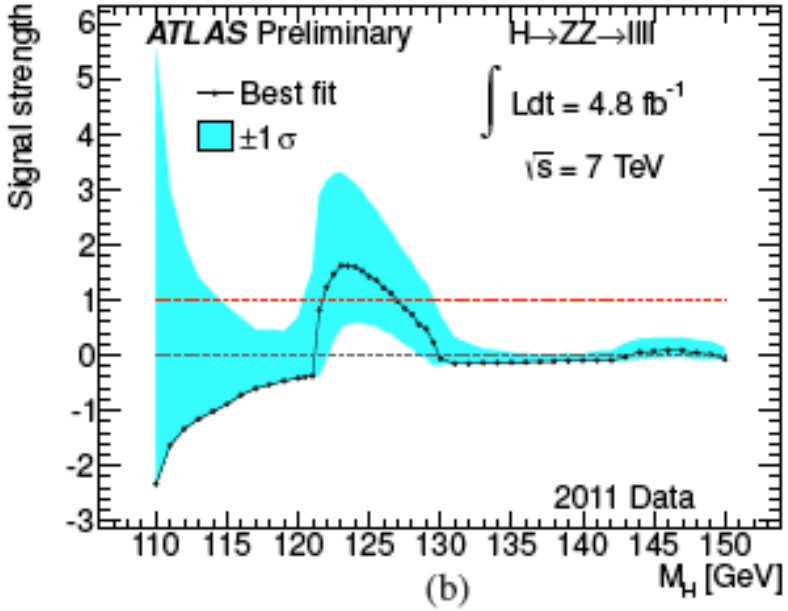
Local p-value from combination



Signal Consistency for Individual Channels







Systematic Uncertainties

Type and source	Uncertainty
Event yield	
Photon reconstruction and identification	$\pm 11\%$
Effect of pileup on photon identification	$\pm 4\%$
Isolation cut efficiency	$\pm 5\%$
Trigger efficiency	$\pm 1\%$
Higgs boson cross section	$+15\%/-11\%$
Higgs boson p_{T} modeling	$\pm 1\%$
Luminosity	$\pm 3.9\%$
Mass resolution	
Calorimeter energy resolution	$\pm 12\%$
Photon energy calibration	$\pm 6\%$
Effect of pileup on energy resolution	$\pm 3\%$
Photon angular resolution	$\pm 1\%$
Migration	
Higgs boson p_{T} modeling	$\pm 8\%$
Conversion reconstruction	$\pm 4.5\%$

- **Largest uncertainties:**
  - **Photon reconstruction and identification efficiency**
  - **Theoretical uncertainty on Higgs cross section**
  - **Calorimeter energy resolution**

The Large Hadron Collider (LHC)